# EXHIBIT 3

# U.S. Patent No. 7,177,369 ("'369 Patent")

**Accused Products (5G NR RAN Solutions / 5G NR cellular base stations)**

For each and every claim identified below, the Accused Products include Defendant's current, past, and future 5G NR cellular base stations and 5G NR Radio Access Network (RAN) solutions utilizing the 3GPP 5G NR Standard Release 15, Release 16, Release 17, or later releases that are provided to Defendant from Nokia or Ericsson (collectively, the "Accused Products").[1] The charts below describe representative products/instrumentalities including (i) Nokia RAN solutions, including 5G NR RAN solutions with MU MIMO; and (ii) Ericsson RAN solutions, including 5G NR RAN solutions with MU MIMO; all of which perform beamforming in accordance with the 5G NR standard.

The following charts apply to each Accused Product because, as described below, each '369 Accused Product implements MU-MIMO and SU-MIMO wireless beamforming technology – including, but not limited to, functionality set forth in the 3GPP 5G NR Release 15 (and/or Release 16, Release 17, etc.) Standard, a communications Standard to which each Accused Product is advertised as compliant – in a manner that causes each Accused Product to function in substantially the same manner with respect to the Asserted Claims, such as asserted claim 1. The Asserted Claims are limited to method claims, Claims 1-7, 9-10, 12-14, 15, 19, 21, 28, 32-33, 35-37, 41.

Different Releases or versions of the relevant 3GPP documents or specifications may be cited herein, or relevant specification documents may be cited without reference to a specific release, but in each case it should be understood that unless otherwise indicated or shown, Defendant requires that each Accused Product comply with the specifications in relevant part as described below. Defendant furthermore configures and operates each Accused Product to operate in an infringing mode as described below.

Each claim limitation is literally infringed by each Accused Product. However, to the extent any claim limitation is not met literally, it is nonetheless met under the doctrine of equivalents because the differences between the claim limitation and each Accused Product would be insubstantial, and each Accused Product performs substantially the same function, in substantially the same way, to achieve the same result as the claimed invention. Notably, Defendant has not yet articulated which, if any, particular claim limitations it believes are not met by the Accused Products. Plaintiff reserves the right to expound on theories under the doctrine of equivalents upon receiving notice of whether and to what extent infringement of any claim limitations are disputed.

[1] Ericsson and Nokia are providers for AT&T. *See, e.g.,* Answer in Intervention filed by Ericsson Inc. in *Finesse Wireless LLC v. AT&T Mobility LLC* (Defendant), *Ericsson Inc.* (Movant-Intervenor), Case No. 2:21-cv-00316-JRG (Lead Case), Dkt. 37 (E.D. Texas Sept. 29, 2021). *See, e.g.,* Answer filed by Nokia of America Corporation in Intervention in *Finesse Wireless LLC v. AT&T Mobility LLC* (Defendant), *Ericsson Inc.* (Movant-Intervenor), Case No. 2:21-cv-00316-JRG (Lead Case), Dkt. 34, Dkt. 35 (E.D. Texas Sept. 29, 2021).

## Claim 1

| Issued Claim 1 | Identification |
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| 1[pre]: A method comprising: | To the extent the preamble is limiting, each of the Accused Products performs a method of claim 1.<br><br>Each of the Accused Products comprises a Radio Access Network (RAN) system for providing communications in a 5G NR network.<br><br>Each of the Accused Products is a 5G NR Radio Access Network (RAN) base station / solution with MU MIMO, SU MIMO or Massive MIMO and beamforming using procedures specified in 5G NR IEEE Technical Specifications such as TS 38.211, and TS 38.213 and TS 38.214.<br><br>For example, Defendant deploys and uses 5G RAN Solutions by vendors Ericsson and Nokia, which are representative products. These 5G RAN Solutions are 5G NR cellular radio access network base stations / systems comprising antenna arrays, beamformers, and MIMO transceivers for performing MU MIMO, SU MIMO, massive MIMO and/or beamforming in 5G networks, and the accused systems include the installed components for the 5G NR RAN solution systems deployed by Defendant. Throughout these claim charts, the exemplary Accused Products/Instrumentalities will be referred to as 5G RAN Solutions and/or as the Nokia 5G NR RAN Solution (e.g., Nokia 5G Radio solution including AirScale active antennas, baseband, radio, RF module) or Ericsson 5G NR RAN Solution (e.g. Ericsson Advanced Antenna Systems for 5G Networks RAN Solution), all of which are exemplary systems that function in substantially the same manner with respect to the Asserted Claims, and all of which are described in the charts below. In the chart for the preamble of claim 1, several descriptions of these RAN Solutions have been included. References to these RAN Solutions in subsequent claim limitations and/or for other asserted claims are a reference back to and incorporated by reference to the descriptions of the RAN Solutions set forth here or in the documentation referenced here.<br><br>The Ericsson 5G NR RAN Solution is described as the Ericsson Advanced Antenna Systems for 5G in the Ericsson White Paper on Advanced Antenna Systems for 5G Networks (publication, including contributors Peter von Butovitsch, David Astely, Christer Friberg, Anders Furuskär, Bo Göransson, Billy Hogan, Jonas Karlsson and Erik Larsson): |

| Issued Claim 1 | Identification |
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| | See https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks (also available at https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks):<br><br>***Key terms***<br>**AAS radio** = Hardware unit that comprises an antenna array, radio chains and parts of the baseband, all tightly integrated to facilitate AAS features<br>**AAS feature** = A multi-antenna feature (such as beamforming and MIMO) that can be executed in the AAS radio, in the baseband unit or both<br>**AAS** = AAS radio + AAS features<br>**Conventional system** = Passive antenna + remote radio unit comprising a low number (2, 4 or 8) of radio chains<br>**Dual-polarized antenna element** = Combination of two antenna elements with orthogonal polarizations with the purpose of enabling diversity and doubling the number of antenna elements on a given physical area<br><br>**What is an advanced antenna system?**<br>An advanced antenna system (AAS) is a combination of an AAS radio and a set of AAS features. An AAS radio consists of an antenna array closely integrated with the hardware and software required for transmission and reception of radio signals, and signal processing algorithms to support the execution of the AAS features. Compared to conventional systems, this solution provides much greater adaptivity and steerability, in terms of adapting the antenna radiation patterns to rapidly time-varying traffic and multi-path radio propagation conditions. In addition, multiple signals may be simultaneously received or transmitted with different radiation patterns.<br><br>***Multi-antenna techniques***<br>Multi-antenna techniques, here referred to as AAS features, include beamforming and MIMO. Such features are already used with conventional systems in today's LTE networks. Applying AAS features to an AAS radio results in significant performance gains because of the higher |

| Issued Claim 1 | Identification |
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| | degrees of freedom provided by the larger number of radio chains, also referred to as Massive MIMO.<br><br>***Beamforming***<br>When transmitting, beamforming is the ability to direct radio energy through the radio channel toward a specific receiver, as shown in the top left quadrant of **Figure 1**. By adjusting the phase and amplitude of the transmitted signals, constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput. Similarly, when receiving, beamforming is the ability to collect the signal energy from a specific transmitter. The beams formed by an AAS are constantly adapted to the surroundings to give high performance in both UL and DL.<br><br>Ericsson's white paper further describes deployment scenarios of Ericsson 5G NR RAN Solutions. *See id. See also* Bo Göransson, Ph.D., Ericsson, 5G – The Multi Antenna Advantage (Oct. 6, 2016), at 15, 30-32, available at http://www.1com.net/wp-content/uploads/2018/05/5G-multi-antenna-advantage.pdf<br><br>---<br><br>The Nokia 5G NR RAN Solution is described as a Nokia 5G Radio Access Network solution with AirScale radio and baseband products, including components such as AirScale active antennas / 8T8R, 32T32R or 64T64R massive MIMO antennas. Deployments can include baseband unit, radio, smart hub, remote radio heads, RF module, and one or more additional components, which supports massive MIMO using e.g., Nokia ReefShark system-on-chip technology.<br><br>See https://www.nokia.com/networks/mobile-networks/airscale-radio-access/: |

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| | # Overview<br><br>Nokia AirScale radio access provides efficient and scalable mobile network coverage and capacity – for 2G, 3G, 4G and 5G with common Single RAN hardware, software, management and services.<br><br>AirScale radio and baseband products—powered by Nokia unique ReefShark System on Chip (SoC) technology—raise the bar for radio and baseband performance and capacity, while ensuring compact form factors and energy efficiency.<br><br>Whether nationwide coverage, extreme network capacity for dense metropolitan areas, tailored enterprise connectivity or efficient in-building coverage, the AirScale portfolio caters for all requirements, with common and modular platforms for optimized network total cost of ownership (TCO). |

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<br>See https://www.nokia.com/networks/mobile-networks/airscale-radio-access/active-antennas/:
<br>The AirScale active antenna portfolio includes a full range of high-performance beamforming products ensuring the most space- and</td></tr>
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| Issued Claim 1 | Identification |
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| | energy-efficient site solutions. The portfolio supports the numerous frequency bands in use around the World as well as fulfilling operators' unique and varied deployment needs.<br>**Massive MIMO Adaptive Antennas**<br>Our AirScale massive MIMO Adaptive Antennas portfolio includes 32TRX and 64TRX for the TDD 4G and 5G mid-bands and dual-band 16TRX for FDD bands. Each enabling the deployment of beamforming optimized solutions covering all deployment scenarios, from dense-urban capacity to wide-area coverage.<br>**New generation Massive MIMO Adaptive Antennas**<br>Our AirScale massive MIMO Adaptive Antennas portfolio includes 32TRX and 64TRX for the TDD 4G and 5G mid-bands and dual-band 16TRX for FDD bands. These enable the deployment of beamforming optimized solutions covering all deployment scenarios, from dense-urban capacity to wide-area coverage.<br><br>Powered by Nokia new generation ReefShark System on Chip (SoC), these new generation massive MIMO antennas are light in weight and industry leading at 17 kilograms. This simplifies deployment considerations and eases installation, speeding-up the rollout of 5G.<br><br>These new designs also support high RF bandwidths, up to 400 MHz, making them ideal for covering fragmented spectrum or network sharing use cases. The ability to support high bandwidth can mean the difference between deploying one or multiple antennas.<br><br>Available in both 32TRX and 64TRX configurations, these industry leading antennas are the ideal choice for all 5G network deployments, delivering high-performance and high-efficiency, while also simplifying site solutions. |

| Issued Claim 1 | Identification |
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| | **New 32TRX massive MIMO antennas**<br>Industry leading solutions, supporting both 400 MHz RF bandwidth and the lightest weight, 17kg<br>**New 64TRX massive MIMO antennas**<br>400 MHz RF bandwidth and high power for maximum capacity and coverage<br>**Powered by new generation Nokia ReefShark SoCs**<br>The foundation for high RF bandwidth and high performance<br><br>See also: https://www.nokia.com/networks/mobile-networks/airscale-radio-access/baseband/: |

| Issued Claim 1 | Identification |
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| | Space- and energy-efficient, high-performance baseband processing for 2G, 3G, 4G and 5G leveraging common systems for all radio cells on low, mid and high (millimeterWave) frequency bands.<br>**AirScale System Module**<br>This baseband module is designed to be agile and enable long-term network evolution. The in-node modularity of the AirScale System Module is key to lean entry and decoupled scalability of the compute power for radio access network layers 1, 2, and 3 and integrated transport functionality – essential for the rapidly changing traffic requirements of new use cases and deployment scenarios of the 5G era.<br>The AirScale System Module simplifies 2G, 3G, 4G and 5G Single RAN deployments, streamlines multi-band sites and powers multi-site baseband hotels.<br>The concept of in-node scalability through addition and coexistence of Single RAN plug-in cards for base and high capacity requirements optimizes total cost of ownership (TCO). Plugging-in the latest cards, when and where additional frequency layers or network densification demand the extra capacity, ensures access to the latest high-performance, energy efficient technology, while maximizing the use phase of the installed base.<br>* * * |

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| | # Nokia AirScale baseband plug-in cards – include AirScale Chinook, AirScale Fremantle and AirScale Ostro<br><br>***Scaling capacity made flexible and efficient***<br><br>The latest AirScale baseband plug-in cards drive capacity up to 84 Gbps throughput and 90,000 simultaneously connected users. This is the capacity to drive 5G forward, towards more immersive user experiences and advanced enterprise use cases. Thanks to the use of the latest technology, these cards are highly efficient and decouple traffic growth from power consumption.<br><br>• Leverage the modularity of AirScale baseband: new and earlier plug-in cards work together – ensuring latest SoC injection into the installed base<br>• Granular in-node composability: the right upgrade steps<br>• Common system (Single RAN) for 2G, 3G, 4G and 5G.<br><br>See https://www.nokia.com/networks/mobile-networks/airscale-radio-access/radio/:<br><br>## AirScale Radio<br><br>The Nokia AirScale radio portfolio supports all radio access technologies 2G, 3G, FDD and TDD 4G and 5G, as well as the numerous frequency bands around the world. |

| Issued Claim 1 | Identification |
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| | With a wide choice of performance characteristics, including RF power outputs, antenna port configurations and compact, easy to deploy form factors, these radios are in service with operators all over the World.<br>**New generation 8T8R remote radio heads – introducing the AirScale Osprey portfolio**<br><br>Our AirScale Osprey portfolio of 8T8R radios uses the same, latest Nokia ReefShark SoC technology as the new massive MIMO antennas. This enables efficient 5G mid-band everywhere.<br><br>The new AirScale Osprey 8 remote radio with beamforming, delivers a total RF power output of 320 Watts across several operating modes. Combined with a low weight compact form-factor and multiple mounting options this high-performance radio offers deployment flexibility across a wide range of use cases.<br><br>It also supports high RF bandwidths, making it ideal for deployment in instances of fragmented spectrum or in network sharing use cases. The supported bandwidth can mean the difference between the deployment of one or multiple radios. This enables leaner sites and lower costs.<br>…<br>Each of the Ericsson and Nokia 5G NR RAN solutions can be deployed as a 5G NR base station. 3GPP standards documents such as TS 38.300 describe aspects of the operations of the eNodeB/ng-eNodeB and gNodeB and associated components of the Accused Products/Instrumentalities. |

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<h2>4.1 Overall Architecture</h2>
An NG-RAN node is either:
- a gNB, providing NR user plane and control plane protocol terminations towards the UE; or
- an ng-eNB, providing E-UTRA user plane and control plane protocol terminations towards the UE.
The gNBs and ng-eNBs are interconnected with each other by means of the Xn interface. The gNBs and ng-eNBs are also connected by means of the NG interfaces to the 5GC, more specifically to the AMF (Access and Mobility Management Function) by means of the NG-C interface and to the UPF (User Plane Function) by means of the NG-U interface (see TS 23.501 [3]).
NOTE: The architecture and the F1 interface for a functional split are defined in TS 38.401 [4].
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| Issued Claim 1 | Identification |
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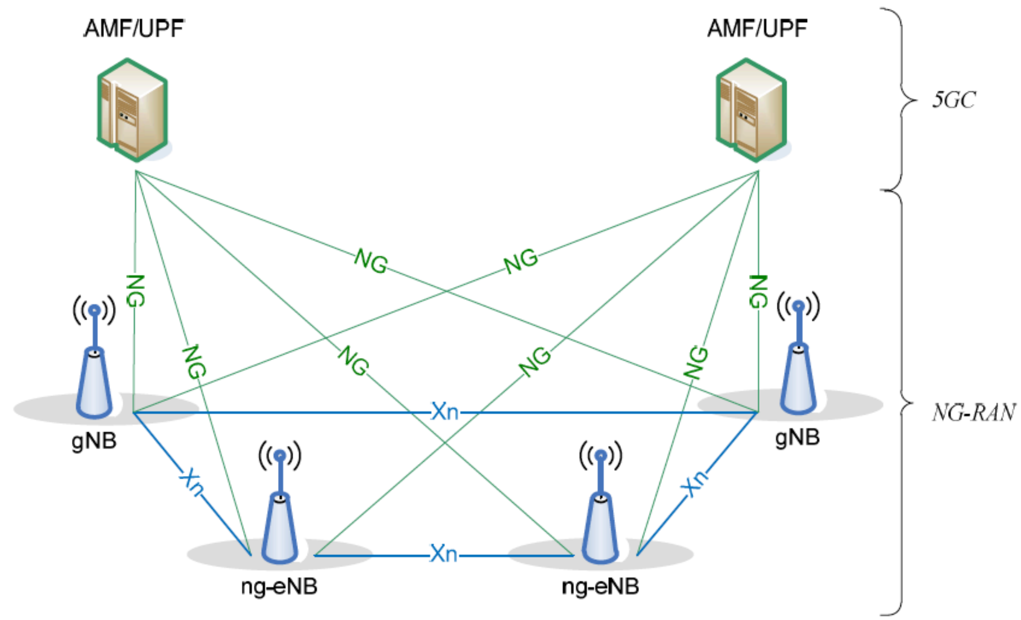
| | The NG-RAN architecture is illustrated in Figure 4.1-1 below.<br><br>**Figure 4.1-1: Overall Architecture**<br>(3GPP TS 38.300 v17.2.0, § 4.1) |

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| 1[a] identifying at least one multipath transmission delay within a reverse path data signal received from a receiving device, | Each accused product performs a method comprising 1[a] identifying at least one multipath transmission delay within a reverse path data signal received from a receiving device, 1[b] determining at least one forward path pre-equalization parameter based on said at least one transmission delay, and 1[c] modifying a forward path data signal that is to be transmitted to the receiving device based on said at least one forward path pre-equalization parameter, where said modifying includes selectively setting different transmission power levels for at least two Orthogonal Frequency Division Multiplexing (OFDM) tones in said forward path data signal.<br><br>As an initial matter, each of the Accused Products comprises a 5G NR RAN base station that includes antenna array and transceiver configured to transmit and receive electromagnetic signals using the antenna. For example, the Ericsson 5G NR RAN Solution is described as an Ericsson Advanced Antenna Systems for 5G in the Ericsson White Paper on Advanced Antenna Systems for 5G Networks (publication, including contributors Peter von Butovitsch, David Astely, Christer Friberg, Anders Furuskär, Bo Göransson, Billy Hogan, Jonas Karlsson and Erik Larsson). The transceiver coupled to the antenna array and configured to transmit and receive electromagnetic signals using the antenna is described as integrated in the AAS radio: See https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks (also available at https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks). The materials in the charts also illustrate that the Nokia RAN Solution includes the RAN base station functionality for communications.<br><br>The Ericsson 5G NR and Nokia 5G NR base stations practice DL / UL beamforming and/or DL / UL MIMO for 5G NR communications. The base station receives “a reverse path data signal received from a receiving device” including one or more uplink transmissions from a UE via one or more antenna elements. As an example, the base station may receive a reverse path data signal from a “receiving device,” which may be a client device / user equipment (UE) that operates in accordance with 3GPP 5G NR.<br><br>The Ericsson and Nokia base stations identify multipath transmission delays in the channel with channel estimation. They may use one or more channel estimation procedures, including by acquiring channel knowledge based on UE feedback and/or based on DL/ UL channel estimation using received uplink transmission signals, and/or a combination of techniques. Using one or more channel estimation techniques, the 5G NR base station performs 1[a] identifying at least one multipath transmission delay within a reverse path data signal received |

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| | from a receiving device, 1[b] determining at least one forward path pre-equalization parameter based on said at least one transmission delay, and 1[c] modifying a forward path data signal that is to be transmitted to the receiving device based on said at least one forward path pre-equalization parameter, where said modifying includes selectively setting different transmission power levels for at least two Orthogonal Frequency Division Multiplexing (OFDM) tones in said forward path data signal. Having determined forward path pre-equalization parameters through one or more channel estimation techniques, the 5G NR base station modifies a forward path data signal that is to be transmitted to the receiving device by selectively setting different transmission power levels, or amplitudes, for at least two OFDM tones. For example, the 5G NR base station uses precoding to adjust the transmit power and perform amplitude scaling on at least two OFDM tones, e.g., using beamforming, as further described herein. The 5G NR base station performs transmit power pre-equalization based on channel estimation procedures including as defined in 3GPP 5G NR technical specifications and as described in relevant materials.<br><br>Channel estimation procedures for MIMO beamforming by 5G NR base stations is described by 5G NR base station vendors, such as Ericsson. As Ericsson explains, "When transmitting, beamforming is the ability to direct radio energy through the radio channel toward a specific receiver, as shown in the top left quadrant of Figure 1. By adjusting the phase and amplitude of the transmitted signals, constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput. Similarly, when receiving, beamforming is the ability to collect the signal energy from a specific transmitter. The beams formed by an AAS are constantly adapted to the surroundings to give high performance in both UL and DL." Further, as Ericsson explains, "Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them. For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell. [For DL beamforming, t]here are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation[, also referred to as UL sounding]…" Channel estimation involves identifying a multipath transmission delay within a reverse path data signal from UE and determining forward path pre-equalization parameters based on the |

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| | transmission delay. DL transmission is modified by the forward path pre-equalization parameters to adjust the transmit power levels for different OFDM tones. These channel estimation procedures and their use is explained in greater detail as to the Ericsson 5G NR RAN Solution / Ericsson Advanced Antenna Systems for 5G in the Ericsson White Paper on Advanced Antenna Systems for 5G Networks (publication, including contributors Peter von Butovitsch, David Astely, Christer Friberg, Anders Furuskär, Bo Göransson, Billy Hogan, Jonas Karlsson and Erik Larsson). Further descriptions are reproduced in the chart below. See https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks (also available at https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks).<br><br>Each accused product performs a method comprising 1[a] identifying at least one multipath transmission delay within a reverse path data signal received from a receiving device.<br><br>As one example, the accused products/instrumentalities identify at least one multipath transmission delay within a reverse path data signal received from a receiving device corresponding to a user equipment device. As an example, the Nokia or Ericsson RAN solution includes at least a gNB base station that communicates with user equipment devices. The gNB is configured to receive a Sounding Reference Signal (SRS) when the user equipment device transmits a Sounding Reference Signal (SRS) (e.g., "reverse path data signal"). The gNB uses the SRS transmitted by the user equipment device to e.g. estimate the channel (e.g., channel frequency response, channel impulse response, estimated phase offset, estimated amplitude offset, complex number, phase delay, multipath propagation delay) ("identifying at least one multipath transmission delay") on at least a subset of the frequency tones.<br><br>In this example relating to SRS, the base station elicits Sounding Reference Signals from the UE mobile device. For example, the base station can configure multiple antenna ports for SRS. For example, the UE can transmit SRSs using one or multiple antenna elements and one or multiple layers / streams and the base station can receive SRSs via one or more antenna elements. For example, the base station receives SRS using different beams and/or layers and/or antenna. Once the gNB receives SRSs, it processes the received SRSs to determine information about the channel and identify multipath transmission delay. For example, channel estimation using |

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| | received SRS can be used for DL or UL precoding and beamforming. For example, channel estimation procedures using received SRS can be used to determine precoding and/or PMI to be used for DL or UL. The base station transmits signals to the UE with precoding that is determined using channel estimation. The base station processes the received SRS to determine information about the channel and to identify a multipath transmission delay within the reverse path data signal from the UE, and to determine how to modify a forward path data signal that is to be transmitted to the UE by determining precoding that adjusts transmit power on at least two OFDM tones, through the 5G NR beamforming functionalities, such as for TDD. Channel estimation with SRS for TDD and/or FDD systems identifies at least one multipath transmission delay parameter by identifying the multipath channel response.<br><br>As another example, the base station also supports identifying multipath transmission delays in signals from the UEs received in response to CSI-RS. See, e.g., Ericsson White Paper entitled "Massive MIMO for 5G networks," available at https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks ("To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station."). For example, the cellular base station sends a CSI-RS signal to the connected UE mobile devices, and the UEs then measure and report back channel state information as feedback to the cellular base station. For example, CSI-RS is a standardized aspect of 5G NR that requires base stations to generate CSI-RS signals for transmission and then the UEs respond to the CSI-RS reference signal with CSI feedback to the base station. The CSI feedback can be sent, for example, using multiple layers or streams and multiple antennas on, e.g., PUSCH with data and e.g. on PUCCH. As an example, see the descriptions for Type I & II Codebook and Enhanced Type II codebook for e.g. 1-layer and 2-layer CSI reporting in 3GPP TS 38.214 § 5.2.2 and § 6. The base station processes the received CSI feedback signals ("reverse path data signal") to determine information about the channel and to identify a "multipath transmission delay" within the reverse path data signal, and to determine how to modify a forward path data signal that is to be transmitted to the UE by determining precoding that adjusts transmit power levels on at least two OFDM tones. As an example, the base station determines a Type II or Enhanced Type II precoding matrix and determines layer configuration and precoding for beamforming transmissions to UE, and this process corresponds to determining forward path pre-equalization parameter based on the |

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| | transmission delay, and modifying a forward path data signal that is to be transmitted to the UE by setting different transmit power levels for at least two OFDM tones in the forward path data signal. For example, in downlink beamforming in FDD systems, the gNB base station expects that the user equipment device makes Channel State Information (CSI) measurements such as the Precoding Matrix Indicator (PMI) and transmits the PMI to the gNB. The gNB receives the CSI measurements such as PMI in a reverse path data signal received from the user equipment device. The gNB identifies at least one multipath transmission delay in the reverse path data signal containing the CSI measurements such as PMI. The gNB determines at least one forward path pre-equalization parameter based on the transmission delay. PMI is an index to a set of coefficients ("forward path pre-equalization parameter") that are applied to the data stream to e.g. form a beam toward the device. The base station determines the DL precoding weights / coefficients to apply based on the identified multipath transmission delay.<br><br>As yet another example, the Ericsson and/or Nokia RAN Solutions may use analog beamforming or combination of analog and digital beamforming. For example, the RAN Solution also identifies at least one multipath transmission delay in a reverse path data signal when determining antenna array element coefficients by evaluating signals received on the elements of the array (e.g., as only one example, evaluating received SRS from user equipment). The base station determines at least one forward path pre-equalization parameter (e.g., analog domain and digital domain coefficients / complex numbers (e.g., amplitude, phase) channel parameters, e.g., for beamforming or MIMO, that are applied to downlink transmission signals) based on identifying the multipath transmission delay. These forward path pre-equalization parameters (e.g., analog domain and digital domain coefficients / complex numbers (e.g., amplitude, phase) channel parameters, e.g., for beamforming or MIMO, that are applied to downlink transmission signals) selectively set different transmission power levels for at least two OFDM tones.<br><br>Claim limitation 1[a] is literally infringed by each Accused Product. However, to the extent claim limitation 1[a] is not met literally, it is nonetheless met under the doctrine of equivalents because the differences between the claim limitation and each Accused Product would be insubstantial, and each Accused Product performs substantially the same function, in substantially the same way, to achieve the same result as the claimed invention. For example, channel estimation on SRS or identifying PMI in a reverse path data signal from the UE |

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| | performs substantially the same function of determining and identifying at least one multipath transmission delay in substantially the same way of determining the multipath channel response from uplink transmission to achieve substantially the same result of computing forward path pre-equalization parameters. The channel estimation techniques used to identify multipath transmission delay parameters using SRS or PMI (e.g., enhanced Type II codebook), including, e.g., channel estimate parameters, beam angles, complex numbers, is substantially the same way as identifying at least one multipath transmission delay within a reverse path data signal. For example, channel estimation on baseband signal using FFT is done in substantially the same way as identifying at least one multipath transmission delay within a reverse path data signal. As another example, determining channel estimation, including complex numbers, phase offset between e.g. the known/reference SRS and the received multipath SRS is substantially the same way, including because this determination is caused by and directly linear proportional to multipath transmission delay between the known/reference SRS and received multipath SRS and is for substantially the same purpose of understanding the multipath effects on the received multipath SRS. As another example, determining channel estimation, including complex numbers, phase offset between e.g. the known/reference CSI-RS and the received multipath CSI-RS, and identifying CSI and PMI that is computed based on the difference between the CSI-RS and the received CSI-RS, is substantially the same way, including because this determination is caused by and directly linear proportional to multipath transmission delay between the known/reference CSI-RS and received multipath CSI-RS and is for substantially the same purpose of understanding the multipath effects on the signal and determining forward path pre-equalization parameters based on the multipath. The result is substantially the same. The result is a channel estimate that conveys the multipath propagation delay characteristics of the channel. The channel estimate is used to determine downlink beamforming precoding generating simultaneous beams in a multipath environment where the downlink beamforming precoding parameters (pre-equalization parameters) are selectively adjusted in e.g. phase and amplitude to produce a signal at the user equipment that has ameliorated multipath propagation effects.<br><br>See technical paper entitled "5G 3GPP-like Channel Models for Outdoor Urban Microcellular and Macrocellular Environments," by Nokia, AT&T et al.: |

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| | 1) UMi: In the double-directional channel model, the multipath components are described by the delays and the directions of departure and the direction of arrival. Each multipath component is scaled with a complex amplitude gain. Then the double directional channel impulse response is composed of the sum of the generated double-directional multipath components. The double directional channel model provides a complete omnidirectional statistical spatial channel model (SSCM) for both LOS and NLOS scenarios in the UMi environment. These results are currently analyzed based on the ray-tracing results, which is compared with the measurement campaign done in the same urban area. The final results will be derived from both the measurement and ray-tracing results. For fast-fading modeling, the ray-tracing based method is useful to extend the sparse empirical datasets and to analyze the channel characteristics in both outdoor and indoor environments.<br><br>See https://ptolemy.berkeley.edu/eecs20/week12/freqResponseDT.html:<br><br>**Frequency Response and Impulse Response**<br><br>Recall that if an LTI system $H$: [$DiscreteTime \to Reals$] $\to$ [$DiscreteTime \to Reals$] has impulse response $h$: $DiscreteTime \to Reals$, and if the input is $x$: $DiscreteTime \to Reals$, then the output is given by the convolution sum<br><br>$y(n) = \sum_{(m = -\infty \text{ to } \infty)} h(m)\, x(n-m)$<br><br>Suppose that the input is a complex exponential function, where for all $n \in Integers$,<br><br>$x(n) = e^{j\omega n}$.<br><br>Then<br><br>$y(n) = \sum_{(m = -\infty \text{ to } \infty)} h(m) e^{j\omega (n-m)}$<br><br>$= e^{j\omega n} \sum_{(m = -\infty \text{ to } \infty)} h(m) e^{-j\omega m}$<br><br>Recall further that when the input is the complex exponential with frequency ω, then the output is given by |

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| | $$y(n) = H(\omega)\, e^{j\omega n}$$ where $H(\omega)$ is called the frequency response. Comparing these two expressions for the output we see that the frequency response is related to the impulse response by $$H(\omega) = \sum_{(m = -\infty \text{ to } \infty)} h(m) e^{-im\omega}.$$ $H(\omega)$ is called the **discrete-time Fourier transform (DTFT)** of $h(n)$. We will study the DTFT in more detail shortly and will examine its relationship to the Fourier series. For now, however, just notice that the impulse response fully defines the frequency response, and in principle, if you know the impulse response, you can calculate the frequency response.<br><br>See Ericsson White Paper entitled "Massive MIMO for 5G networks," updated Feb. 2023: (available at https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks):<br><br>***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.<br><br>DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need |

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| | to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics.<br><br>See https://www.techplayon.com/nr-sound-reference-signal-nr-srs/:<br><br>**5G NR Sounding Reference Signal (NR-SRS)**<br><br>In NR there are two types of Reference Signal in UL which gives information about the channel quality.<br><br>1. DMRS:- Demodulation Reference Signal<br>2. SRS:- Sounding Reference Signal<br><br>With the help of above two RS, gNB takes smart decisions for resource allocation for uplink transmission, link adaptation and to decode transmitted data from UE. SRS is a UL reference |

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| | signal which is transmitted by UE to Base station. SRS gives information about the combined effect of multipath fading, scattering, Doppler and power loss of transmitted signal.<br><br>Hence Base Station estimates the channel quality using this reference signal and manages further resource scheduling, Beam management, and power control of signal. So SRS provides information to gNB about the channel over full bandwidth and using this information gNB takes decision for resource allocation which has better channel quality comparing to other Bandwidth regions.<br><br>See 3GPP TS 38.214 version 15.16.0 (2022-03):<br><br>6.2 UE reference signal (RS) procedure<br>6.2.1 UE sounding procedure<br>The UE may be configured with one or more Sounding Reference Signal (SRS) resource sets as configured by the higher layer parameter *SRS-ResourceSet*. For each SRS resource set, a UE may be configured with $K \geq 1$ SRS resources (higher layer parameter *SRS-Resource*), where the maximum value of K is indicated by UE capability [13, 38.306]. The SRS resource set applicability is configured by the higher layer parameter *usage* in *SRS-ResourceSet.* When the higher layer parameter *usage* is set to 'beamManagement', only one SRS resource in each of multiple SRS sets may be transmitted at a given time instant, but the SRS resources in different SRS resource sets with the same time domain behaviour in the same BWP may be transmitted simultaneously.<br>For aperiodic SRS at least one state of the DCI field is used to select at least one out of the configured SRS resource set(s).<br>The following SRS parameters are semi-statically configurable by higher layer parameter *SRS-Resource*.<br>- *srs-ResourceId* determines SRS resource configuration identity.<br>- Number of SRS ports as defined by the higher layer parameter *nrofSRS-Ports* and described in Subclause 6.4.1.4 of [4, TS 38.211].<br>- Time domain behaviour of SRS resource configuration as indicated by the higher layer parameter *resourceType*, which may be periodic, semi-persistent, aperiodic SRS transmission as defined in Subclause 6.4.1.4 of [4, TS 38.211]. |

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| | - Slot level periodicity and slot level offset as defined by the higher layer parameters *periodicityAndOffset-p* or *periodicityAndOffset-sp* for an SRS resource of type periodic or semi-persistent. The UE is not expected to be configured with SRS resources in the same SRS resource set *SRS-ResourceSet* with different slot level periodicities. For an *SRS-ResourceSet* configured with higher layer parameter *resourceType* set to 'aperiodic', a slot level offset is defined by the higher layer parameter *slotOffset*.<br><br>- Number of OFDM symbols in the SRS resource, starting OFDM symbol of the SRS resource within a slot including repetition factor R as defined by the higher layer parameter *resourceMapping* and described in Subclause 6.4.1.4 of [4, TS 38.211].<br><br>- SRS bandwidth $B_{SRS}$ and $C_{SRS}$, as defined by the higher layer parameter *freqHopping* and described in Subclause 6.4.1.4 of [4, TS 38.211].<br><br>- Frequency hopping bandwidth, $b_{hop}$, as defined by the higher layer parameter *freqHopping* and described in Subclause 6.4.1.4 of [4, TS 38.211].<br><br>- Defining frequency domain position and configurable shift, as defined by the higher layer parameters *freqDomainPosition* and *freqDomainShift, respectively,* and described in Subclause 6.4.1.4 of [4, TS 38.211].<br><br>See 3GPP TS 38.211 v15.6.0 (2019-06):<br><br>*6.4.1.4 Sounding reference signal*<br>6.4.1.4.1 SRS resource<br>An SRS resource is configured by the *SRS-Resource* IE and consists of<br>- $N_{\mathrm{ap}}^{\mathrm{SRS}} \in \{1,2,4\}$ antenna ports $\{p_i\}_{i=0}^{N_{\mathrm{ap}}^{\mathrm{SRS}}-1}$, where the number of antenna ports is given by the higher layer parameter *nrofSRS-Ports,* $p_i = 1000 + i$ when the SRS resource is in a SRS resource set with higher-layer parameter *usage* in *SRS-ResourceSet* not set to 'nonCodebook', or determined according to [6, TS 38.214] when the SRS resource is in a SRS resource set with higher-layer parameter *usage* in *SRS-ResourceSet* set to 'nonCodebook'<br><br>- $N_{\mathrm{symb}}^{\mathrm{SRS}} \in \{1,2,4\}$ consecutive OFDM symbols given by the field *nrofSymbols* contained in the higher layer parameter *resourceMapping* |

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| | - $l_0$, the starting position in the time domain given by $l_0 = N_{\text{symb}}^{\text{slot}} - 1 - l_{\text{offset}}$ where the offset $l_{\text{offset}} \in \{0,1,\ldots,5\}$ counts symbols backwards from the end of the slot and is given by the field *startPosition* contained in the higher layer parameter *resourceMapping* and $l_{\text{offset}} \geq N_{\text{symb}}^{\text{SRS}} - 1$<br>- $k_0$, the frequency-domain starting position of the sounding reference signal<br><br>Each accused product performs a method determining at least one forward path pre-equalization parameter based on said at least one transmission delay.<br><br>For example, TDD systems, the multipath transmission delay identified by the gNB using the received SRS symbols, is, by taking advantage of channel reciprocity property of a TDD system, used by the gNB to compute a set of beamforming coefficient parameters ("pre-equalization parameter") that are used for precoding, much like PMI parameters in e.g. FDD systems. These pre-equalization parameters are, as in the PMI approach, applied to the data stream to form a downlink beam. For example, in a TDD system (where UL and DL channels are considered reciprocal), an Ericsson and/or Nokia base station calculates DL precoding weights based on the sounding reference signal that a user transmits in UL.<br><br>For example, the base station may compare the received SRS signal with a local version that is a known SRS reference signal to estimate the channel (e.g., channel multipath delay profile) using, e.g., correlation techniques.<br><br>https://www.sharetechnote.com/html/5G/5G_SRS.html<br><br>**Phase I** - RRC Configuration for SRS<br>This is the phase where gNB determines about SRS configuration (e.g., SRS physical resources, usage, report period timing etc.) and notifies the configuration to UE via RRC messages (e.g., RRCSetup, RRCReconfiguration).<br>**Phase II** - SRS transmission from UE:<br>In this phase, the UE transmits the SRS, which is a predefined signal with known characteristics, at a specific time and frequency. The SRS configuration is provided to the UE by the gNB, and it may vary depending on the cell's conditions and traffic requirements. The UE sends the SRS periodically or aperiodically, as instructed by the gNB, on the uplink (UL) channel. |

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| | **NOTE** : gNB can configure UE to transmit the srs across the full band at once or can configure UE to transmit the srs for a certain segment of the frequency band using the parameter explained in Bandwidth Configuration.<br>**NOTE** : gNB configures how often and at which timing UE should send SRS. gNB would get better and more accurate information as it let UE to transmit more often for wider frequency span, but overhead caused by srs transmission would get higher.<br>**Phase III** - SRS reception at gNB and Analysis:<br>Upon receiving the SRS from the UE, the gNB measures and analyzes the received signal. It estimates the channel state information (CSI) by comparing the received SRS with the known reference signal. The gNB evaluates various parameters, such as the path loss, propagation delay(phase delay), and received signal strength, to understand the current radio environment and channel conditions between the gNB and the UE.<br><br>https://telcomaglobal.com/p/5g-nr-srs-sounding-reference-signals<br><br>**5G NR SRS (Sounding Reference Signals)**<br>Introduction<br>SRS is Sounding Reference Signal is a reference signal transmitted by the UE in the uplink direction which is used by the eNodeB to estimate the uplink channel quality over a wider bandwidth. SRS is a UL reference signal which is transmitted by UE to the base station. SRS gives information about the combined effect of multipath fading, scattering, Doppler, and power loss of the transmitted signal. Sounding reference signals are uplink physical signals employed by user equipment (UE) for uplink channel sounding, including channel quality estimation and synchronization. Unlike Demodulation reference signals (DM-RS), SRS is not associated with any physical uplink channels, and they support uplink channel-dependent scheduling and link adaptation. SRS assist in:<br>• Codebook-based closed-loop spatial multiplexing<br>• Control uplink transmit timing<br>• Reciprocity-based downlink precoding in multi-user MIMO setups<br>• Quasi co-location of physical channels and reference signals<br>In 5G NR, the SRS is transmitted by the UE for uplink channel sounding, which includes channel estimation and synchronization. An NR-SRS is an uplink orthogonal frequency division multiplexing (OFDM) signal filled with a Zadoff-Chu sequence on different subcarriers. For the purposes of communications, the SRS is used for closed-loop spatial multiplexing, uplink transmitting timing control, and reciprocity multi-user downlink precoding. To utilize the channel sounding function, the SRS must |

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| | be known by both the UE and the gNB. UE act as a mobile transmitter and gNB act as a base station receiver.<br><br>Base station estimates the channel quality using this reference signal and manages further resource scheduling, Beam management, and power control of the signal. So SRS provides information to gNB about the channel over the full bandwidth and using this information, gNB takes decisions for resource allocation which has better channel quality as compared to other Bandwidth regions<br><br>As another example, in downlink beamforming in e.g. FDD systems, the Ericsson and/or Nokia gNB base station expects that the user equipment device makes Channel State Information (CSI) measurements such as the Precoding Matrix Indicator (PMI) and transmits the PMI to the gNB. The gNB receives the CSI measurements such as PMI in a reverse path data signal received from the user equipment device. The gNB identifies at least one multipath transmission delay in the reverse path data signal (e.g., the CSI measurements such as, e.g., PMI). The gNB determines at least one forward path pre-equalization parameter based on the transmission delay. For example, PMI is an index to a set of coefficients ("forward path pre-equalization parameter") that are applied to the data stream to e.g. form a beam toward the device. The base station determines the DL precoding weights / coefficients to apply based on the identified multipath transmission delay.<br><br>See Ericsson White Paper entitled Massive MIMO for 5G Networks," dated Feb. 2023:<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by a suitable averaging of UL channel estimate statistics. |

See 3GPP TS 38.214 V15.6.0 (2019-06):

5.2 UE procedure for reporting channel state information (CSI)

5.2.1 Channel state information framework

The time and frequency resources that can be used by the UE to report CSI are controlled by the gNB. CSI may consist of Channel Quality Indicator (CQI), precoding matrix indicator (PMI), CSI-RS resource indicator (CRI), SS/PBCH Block Resource indicator (SSBRI), layer indicator (LI), rank indicator (RI) and/or L1-RSRP.

For CQI, PMI, CRI, SSBRI, LI, RI, L1-RSRP, a UE is configured by higher layers with N≥1 *CSI-ReportConfig* Reporting Settings, M≥1 *CSI-ResourceConfig* Resource Settings, and one or two list(s) of trigger states (given by the higher layer parameters *CSI-AperiodicTriggerStateList* and *CSI-SemiPersistentOnPUSCH-TriggerStateList*). Each trigger state in *CSI-AperiodicTriggerStateList* contains a list of associated *CSI-ReportConfigs* indicating the Resource Set IDs for channel and optionally for interference. Each trigger state in *CSI-SemiPersistentOnPUSCH-TriggerStateList* contains one associated *CSI-ReportConfig*.

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*5.2.2.2 Precoding matrix indicator (PMI)*

5.2.2.2.1 Type I Single-Panel Codebook

For 2 antenna ports {3000, 3001} and the UE configured with higher layer parameter *codebookType* set to 'typeI-SinglePanel' each PMI value corresponds to a codebook index given in Table 5.2.2.2.1-1. The UE is configured with the higher layer parameter *twoTX-CodebookSubsetRestriction*. The bitmap parameter *twoTX-CodebookSubsetRestriction* forms the bit sequence $a_5,...,a_1,a_0$ where $a_0$ is the LSB and $a_5$ is the MSB and where a bit value of zero indicates that PMI reporting is not allowed to correspond to the precoder associated with the bit. Bits 0 to 3 are associated respectively with the codebook indices 0 to 3 for $\upsilon=1$ layer, and bits 4 and 5 are associated respectively with the codebook indices 0 and 1 for $\upsilon=2$ layers.

**Table 5.2.2.2.1-1: Codebooks for 1-layer and 2-layer CSI reporting using antenna ports 3000 to 3001**

| | **Number of layers $\upsilon$** |
|---|---|

| Codebook index | 1 | 2 |
|---|---|---|
| **0** | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$ |
| **1** | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$ |
| **2** | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$ | - |
| **3** | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$ | - |

For 4 antenna ports {3000, 3001, 3002, 3003}, 8 antenna ports {3000, 3001, …, 3007}, 12 antenna ports {3000, 3001, …, 3011}, 16 antenna ports {3000, 3001, …, 3015}, 24 antenna ports {3000, 3001, …, 3023}, and 32 antenna ports {3000, 3001, …, 3031}, and the UE configured with higher layer parameter *codebookType* set to 'typeI-SinglePanel', except when the number of layers $\upsilon \in \{2,3,4\}$ (where $\upsilon$ is the associated RI value), each PMI value corresponds to three codebook indices $i_{1,1}, i_{1,2}, i_2$. When the number of layers $\upsilon \in \{2,3,4\}$, each PMI value corresponds to four codebook indices $i_{1,1}, i_{1,2}, i_{1,3}, i_2$. The composite codebook index $i_1$ is defined by

$$i_1 = \begin{cases} \begin{bmatrix} i_{1,1} & i_{1,2} \end{bmatrix} & \upsilon \notin \{2,3,4\} \\ \begin{bmatrix} i_{1,1} & i_{1,2} & i_{1,3} \end{bmatrix} & \upsilon \in \{2,3,4\} \end{cases}$$

The codebooks for 1-8 layers are given respectively in Tables 5.2.2.2.1-5, 5.2.2.2.1-6, 5.2.2.2.1-7, 5.2.2.2.1-8, 5.2.2.2.1-9, 5.2.2.2.1-10, 5.2.2.2.1-11, and 5.2.2.2.1-12. The mapping from $i_{1,3}$ to $k_1$ and $k_2$ for 2-layer reporting is given in Table 5.2.2.2.1-3. The mapping from $i_{1,3}$ to $k_1$ and $k_2$ for 3-layer and 4-layer reporting when $P_{\text{CSI-RS}} < 16$ is given in Table 5.2.2.2.1-4. The quantities $\varphi_n$, $\theta_p$, $u_m$, $v_{l,m}$, and $\tilde{v}_{l,m}$ are given by

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| | $$\varphi_n = e^{j\pi n/2}$$ $$\theta_p = e^{j\pi p/4}$$ $$u_m = \begin{cases} \begin{bmatrix} 1 & e^{j\frac{2\pi m}{O_2 N_2}} & \cdots & e^{j\frac{2\pi m(N_2-1)}{O_2 N_2}} \end{bmatrix} & N_2 > 1 \\ 1 & N_2 = 1 \end{cases}$$ $$v_{l,m} = \begin{bmatrix} u_m & e^{j\frac{2\pi l}{O_1 N_1}} u_m & \cdots & e^{j\frac{2\pi l(N_1-1)}{O_1 N_1}} u_m \end{bmatrix}^T$$ $$\tilde{v}_{l,m} = \begin{bmatrix} u_m & e^{j\frac{4\pi l}{O_1 N_1}} u_m & \cdots & e^{j\frac{4\pi l(N_1/2-1)}{O_1 N_1}} u_m \end{bmatrix}^T$$ <br>- The values of $N_1$ and $N_2$ are configured with the higher layer parameter *n1-n2*, respectively. The supported configurations of $(N_1, N_2)$ for a given number of CSI-RS ports and the corresponding values of $(O_1, O_2)$ are given in Table 5.2.2.2.1-2. The number of CSI-RS ports, $P_{\text{CSI-RS}}$, is $2N_1N_2$.<br>- UE shall only use $i_{1,2} = 0$ and shall not report $i_{1,2}$ if the value of $N_2$ is 1.<br><br>Each accused product performs a method comprising modifying a forward path data signal that is to be transmitted to the receiving device based on said at least one forward path pre-equalization parameter, where said modifying includes selectively setting different transmission power levels for at least two Orthogonal Frequency Division Multiplexing (OFDM) tones in said forward path data signal.<br><br>Ericsson and Nokia RAN solutions use beamforming for 5G communications. For example, the data symbols of a data stream/layer in a MIMO transmitter are modified by applying a set of coefficients to the said data to form at least one spatial beam. The modification is carried out using the beamformer coefficient parameters (“pre-equalization parameter”), also known as precoder in 3GPP. The beamformer coefficients/precoder parameters (“pre-equalization parameters”) are |

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| | computed based on the estimate of the channel comprising at least one identified multipath transmission delay. For example, with respect to the multipath transmission delay, for example, the channel estimate gives a channel impulse response that relates to the channel frequency response, which in OFDM modulation scheme such as 5G NR relates to the channel frequency response on each tone. The precoding coefficients / parameters relate to the channel estimate. In a frequency selective (multipath) radio propagation channel, the channel frequency response is different on the different frequency tones of the OFDM signal. For example, the precoder/beamformer coefficient parameters applied to the symbols of the different tones are different to accommodate the differences in the channel frequency response on the different tones due to multipath. In 5G, for example, frequency/time resources consist of frequency tones of the OFDM symbols. The allocated resources to a device, so called resource grid, consist of multiple Resource Blocks (RBs), and each RB in turn consists of 12 frequency tones. For example, the frequency tones of a resource grid cover a range of frequency spectrum, over which the channel frequency response varies, requiring different beamformer coefficient/precoder parameter for different tones. For example, the beamformer coefficient/precoder parameters are complex numbers whose amplitude determines the amount of power applied to the tones.<br><br>See https://www.sharetechnote.com/html/5G/5G_CSI_RS_Codebook.html:<br><br>**What is Codebook ?**<br><br>What is Codebook ? It would many different things in different situation, but the meaning of Codebook under the context of CSI-RS is a set of Precoders (a set of Precoding Matrix). Putting it other way, Codebook is a kind of matrix (a matrix having complex value elements) that transform the data bit (PDSCH) to another set of data that maps to each antenna port.<br>… |

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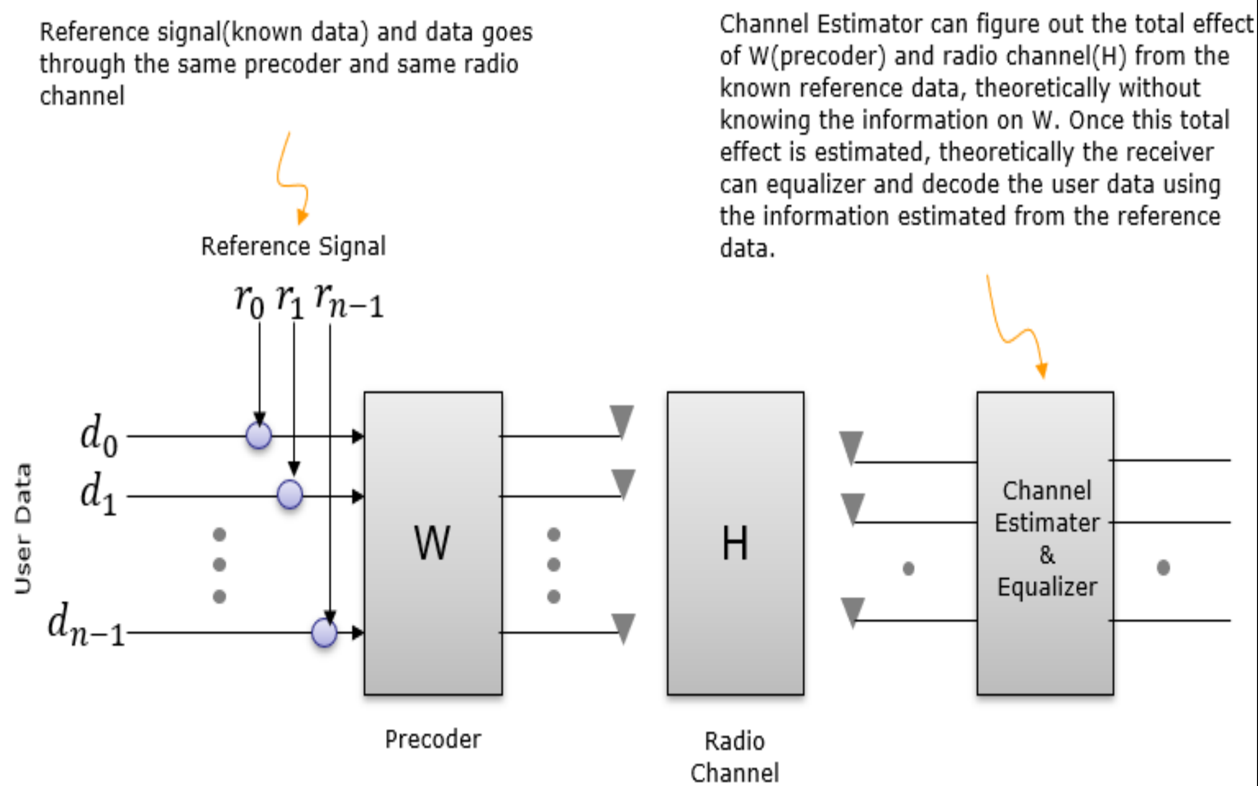
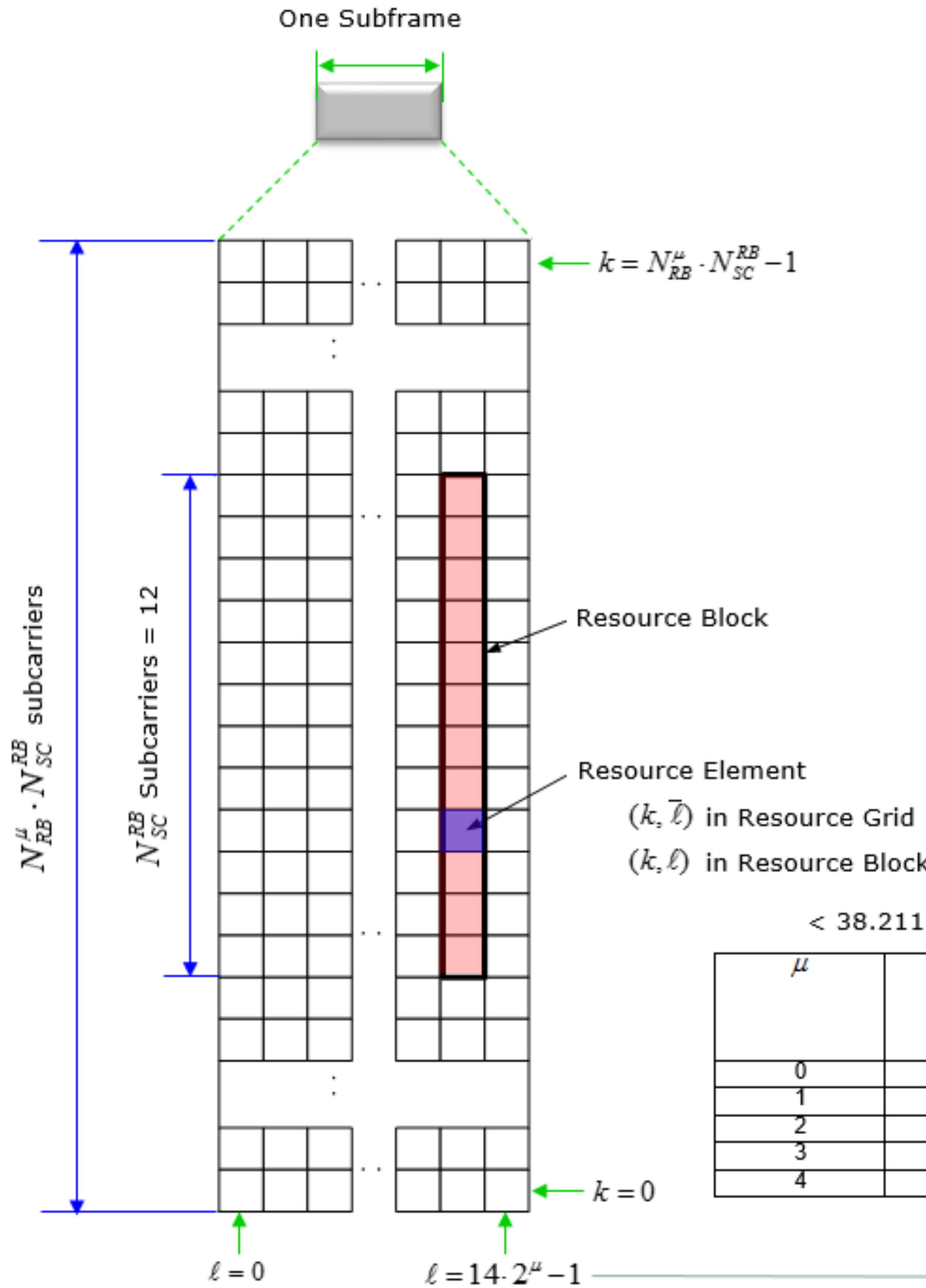
| | <br>See https://www.sharetechnote.com/html/5G/5G_ResourceGrid.html:<br>**Resource Grid**<br>The resource grid for NR is defined as follows. If you just take a look at the picture, you would think it is almost identical to LTE resource grid. But the physical dimension (i.e., subcarrier spacing, number of OFDM symbols within a radio frame) varies in NR depending on numerology. |




< 38.211-Table 4.2.2-1 >

| $\mu$ | Slot configu… 0 | |
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| | $N_{\text{symb}}^{\mu}$ | $N_{\text{fra…}}^{\text{slo…}}$ |
| 0 | 14 | 10 |
| 1 | 14 | 20 |
| 2 | 14 | 40 |
| 3 | 14 | 80 |
| 4 | 14 | 16 |

**Resource Element** : This is same as LTE. It is the smallest unit of the resource grid made up of one subcarrier in frequency domain and one OFDM symbol in time domain.

**Resource Block**: In NR, Resource Block is defined only for frequency domain. 38.211-4.4.4.1 states *'A resource block is defined as 12(N_RB_sc) consecutive subcarriers in the frequency domain'*.
Time domain definition of resource block is a little bit ambiguous. Minimum time domain length in a resource block can be one OFDM symbol, but exact time domain length vary depending SLIV.

**Resource Grid and Antenna port and Numerology** : Basically one resource grid is created for one antenna port and numerology. 38.211-4.2.2 states as follows.

- *There is one set of resource grids per transmission direction (uplink or downlink) with the subscript set to DL and UL for downlink and uplink*
- *There is one resource grid for a given antenna port p , subcarrier spacing configuration u, and transmission direction (downlink or uplink).*

The maximum and minimum number of Resource blocks for downlink and uplink is defined as below (this is different from LTE)

< 38.211 Table 4.4.2-1: Minimum and maximum number of resource blocks.>

| $\mu$ | $N_{RB,DL}^{min,\mu}$ | $N_{RB,DL}^{max,\mu}$ | $N_{RB,UL}^{min,\mu}$ | $N_{RB,UL}^{max,\mu}$ |
|---|---|---|---|---|
| 0 | 24 | 275 | 24 | 275 |
| 1 | 24 | 275 | 24 | 275 |
| 2 | 24 | 275 | 24 | 275 |
| 3 | 24 | 275 | 24 | 275 |
| 4 | 24 | 138 | 24 | 138 |

Ericsson and Nokia base stations receives UL streams/layers. For example, UL-MIMO is supported for several NR Bands including n41 (2496-2690 MHz), n77 (3.3-4.2GHz), n78 (3.3-3.8 GHz), n79 (4.4-5 GHz).

Ericsson and Nokia base stations support precoding. As an example, PUSCH Transform Precoding is specified including the antenna port configuration for PUSCH. Precoding Matrix for

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| | PUSCH for MIMO is also specified. See, e.g., 3GPP TS 38.211 Table 6.3.1.5; 3GPP TS 38.212 Table 7.3.1.1.2. For example, 3GPP TS 38.211 Section 6.1.3.5 describes precoding for the physical uplink shared channel (PUSCH), including single- or multi-layer transmission.<br><br>Base station also transmits DL MIMO streams/layers. PDSCH Transform Precoding and Precoding Matrix for MIMO on DL channels is specified in the 5G NR specifications.<br><br>As another example, the base station uses beams to receive uplink transmissions from the UE. The beams allow the base station to receive a reverse path data signal and identify multipath transmission delay. Once the gNB does so, it determines precoding forward path pre-equalization parameters. With MIMO and beamforming, the 5G NR base station transmits and receives using precoding matrix. Precoding matrix for Type I, Type II, Enhanced Type II Codebooks are described, e.g., in 3GPP TS 38.214 v16.2 Release 16 at §5.2.2. *W* is used to describe the precoding matrix, which can vary based on the number of layers and antenna ports used. For example, the precoding matrix / matrices results in selectively setting different transmission power levels for at least two Orthogonal Frequency Division Multiplexing (OFDM) tones in forward path data signal.<br><br>The 3GPP 5G NR Technical Specifications describe these procedures in detail, and certain relevant portions of the 3GPP 5G NR Technical Specifications are reproduced in the chart below. These procedures are also explained in publications and materials from 5G NR base station equipment vendors such as Ericsson and Nokia, for example, which are reproduced in the chart below. It is also described in secondary sources.<br><br>For example, Ericsson published "How to build high-performing Massive MIMO systems," Billy Hogan, Bo Göransson, Sebastian Faxér, Sibel Tombaz, available athttps://www.ericsson.com/en/blog/2021/2/how-to-build-high-performing-massive-mimo-systems. This article explains that Massive MIMO solutions or advanced antenna systems (AAS) with beamforming features comprises an AAS radio and Massive MIMO features such as beamforming which can be executed by algorithms in the AAS radio or a RAN Compute connected to the AAS radio or both. It further describes the use of channel estimation to understand multipath transmission delay and reshape beams in both time and frequency to modify the transmission power level of multiple OFDM tones: |

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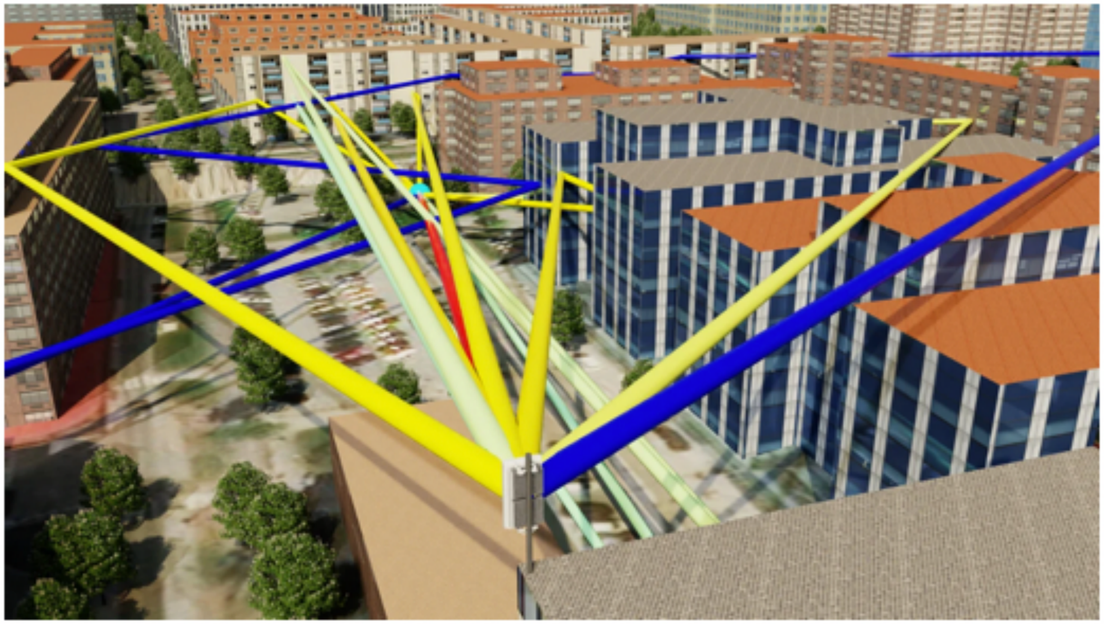
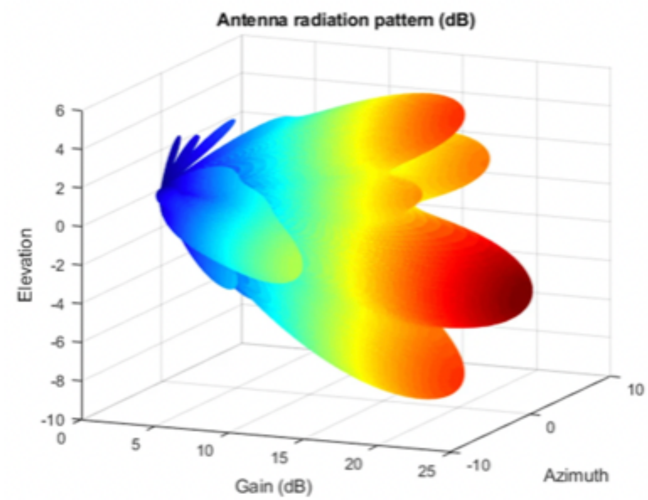
| | "Of course, just being able to focus energy in a fixed direction is not very useful as people typically move around. So, to be able to control the direction and shape of the beams in any way we want in space, we also make the antennas individually controllable with their own radio chains, so we can change the amplitude and phase of their signals separately.<br><br>This gives us numerous coverage and capacity abilities, including:<br><br>• To create multiple beams at the same time<br>• To send and receive radio signals extremely quickly – on a fraction of a millisecond basis – where we want to, while reducing interference in directions where we don´t want that energy to go or come from. All of this, for multiple users simultaneously!<br><br>But - this is no easy task. How do we "form" the right beams to get the most signal energy to the user that we want? People usually think of a beam as a simple concentration of energy that looks like the figure below. You just point it in the direction that you want and that´s all that you need. It is true that you can form beams like that, and they will often work quite well, but they are not always optimal.<br><br>The reason we can do better than a simple beam is that the "radio channel" is a highly complicated environment, since the signal path that travels between the base station and each device reflects off numerous objects causing standing waves and dips that change in time and in frequency at sub millisecond level, as multiple paths arrive at the receiver from all directions, as illustrated in the picture below. |



Think of a choppy ocean… what should the ideal beams look like to navigate this environment with the best performance? To add to the complexity, this channel is different for each of the hundreds of moving devices that are connected within a cell so they each need precisely created beams of their own and of course when we send a beam to one user we don't want to interfere with others.

So, the beams must be highly precise, individual, and continually reshaped every fraction of a millisecond both in time and frequency, based on instant measurements of the radio channel across the spectrum together with large scale calculations to work out and apply the beams to the data we want to send or receive. The gigabits of data that are sent and received over the air interface are practically surfing the radio channel and just as in wave surfing, precise timing is essential to catch the radio waves. If you let your view of the channel information get too old, which happens extremely quickly, you will fall off the wave, and miss the chance to optimize your beamforming

performance. The instantaneous beam that works best can look quite arbitrary as illustrated below but best achieves the goal of getting the energy exactly where we want until we change it for a new beam a fraction a millisecond later.




For CSPs, the result is much greater coverage, much greater network capacity and high end-user speeds over a wider area compared to remote radio unit solutions. The CSP can exploit their valuable spectrum resources to the utmost without vastly increasing the number of sites. This has the benefit of reducing the cost per gigabit per area while preparing CSPs for future traffic growth - they can continue providing outstanding speeds and great coverage as the data traffic load gets heavier.

**The art and science behind Ericsson Advanced Antenna Systems**
We can clearly see the benefits of AAS. However, there are also challenges to realize its full potential:

- **Radio challenges:** Larger bandwidth and more antenna branches drive the need for increased processing capacity, which drives higher power consumption, size and weight at the base station.

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| | • **Beamforming challenges:**<br>  ◦ The radio environment changes on sub-millisecond timeframes as the smartphone moves. Adding to this complexity is of course the hundreds of other devices that connect within the cell.<br>  ◦ The beams must be continually reshaped every fraction of a millisecond, based on instant snapshots of the channel, both in time and frequency.<br>  ◦ To adapt the beams in a complex radio environment for many users simultaneously when using multiple antennas, requires millions of mathematical calculations per second<br><br>To address these challenges, Ericsson adds three key components: **access** to information about the instantaneous radio channel, clever **algorithms** which utilize this information, and the processing power of the Ericsson **silicon**. Fortunately, Ericsson's long experience in the AAS field has ensured that both our hardware design and beamforming algorithms are prepared for this.<br><br>The Ericsson Massive MIMO architecture has been designed to put as much as possible of the beamforming and MIMO processing in the AAS radio itself, close to the antennas and radio channel, where we have **access** to real-time and fine granular information about the radio channel. Therefore, Ericsson is able to do channel estimation and beamforming weight calculations that follow the extremely rapid changes that occur on the radio channel almost instantaneously. You could say that Ericsson Massive MIMO antennas have a fingertip feel of the radio channel and can react to the real-time channel situation with the best possible beams.<br><br>Putting this processing in the radio where it belongs also has other advantages. The fronthaul bit rate from the radio to the RAN Compute is reduced, thus saving costs, and the RAN Compute can concentrate on its own tasks,- for example to schedule users over many cells, and to encode and decode the data bits on the user plane, which must be well protected before they are sent over the air. |

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| | Secondly, we need clever beamforming **algorithms** to act on the channel data. In fact, the way to do the beamforming in 5G is not defined by any 3GPP standard and is completely up to implementation, which means there is a lot of room for innovation and artistic freedom.<br><br>To solve the complex challenge of adapting to time-varying radio channel, we need to generate ultra-precise beamforming by applying different precoder weights to the antenna elements of our array so that after passing through the wireless channel to the target user, the signals from the multiple antennas add up coherently to boost the signal. This is analogous to creating a harmony in music by playing several tones on the piano at certain specific intervals so that when added up they form a pleasant-sounding chord.<br><br>But we simultaneously want to reduce interference to other users by having the signals from the different antenna elements add up destructively, akin to creating a dissonant-sounding chord in music by playing tones with other intervals (like a diminished fifth). The problem to generate optimal beamforming performance to achieve these goals simultaneously then becomes similar to composing a musical arrangement with complex harmonies and passages, while handling multiple instruments simultaneously, both an art and a science! And as we know, it takes both skill and dedication to become a Mozart as it does to master the art of Massive MIMO.<br><br>To generate ultra-precise beamforming, a massive set of complex calculations needs to be performed in real-time, scaling with the number of antennas, the bandwidth and number of users. This adds up to millions of mathematical calculations per second, which requires an extreme processing capability. In addition, it also requires our sophisticated software features and algorithms to make sure that we leverage that hardware in the best way. This can only be achieved with Ericsson **silicon,** system on a chip (SoC) solution, as outlined in the previous blog. It can not only handle all that processing capacity inside the Massive MIMO radio, but also creates much tighter |

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| | integration of components inside the radio. This way, we can build a high-performing radio without adding size, weight or energy consumption.<br><br>As another example, 5G NR beamforming technology is described in secondary sources, such as "MIMO Beamforming Using PMI Type II Precoding," Caroline Jenisha Ruth Mary Pramila Paul Sudhakar, Degree Project in Electrical Engineering, Second Cycle, Stockholm, Sweden 2021, KTH Royal Institute of Technology, available at https://www.diva-portal.org/smash/get/diva2:1618389/FULLTEXT01.pdf. This project lists Carolina Jenisha R P of KTH Royal Institute of Technology as Author with Ericsson AB as Host Company, Medhat Mohammad of Ericsson AB as Supervisor, and Ben Slimane of KTH Royal Institute of Technology as Examiner.<br><br>**2.2.1 Beamforming**<br><br>Focusing the power of all antenna elements combined with the help of beamformers or weights towards one direction is called beamforming as shown in figure 2.2.1. When the angular spread between the BS and UE is zero (i.e.) in the existence LOS or one dominant path the above definition applies. In reality, there exists multiple paths (i.e.) NLOS or multiple paths, which requires *precoding* at the transmitter or receiver. Precoder applies weights on to the antenna element that comprises of amplitude and phase for each antenna element. With the help of weights, the antenna can be electronically steered to radiate in the intended direction by suppressing the power in the other directions. Beamformers can be precoded to radiate in two or more propagating path making use of the diversity gain provided by the fading channel. In general, BF can be considered as a special case of precoding for LOS path. The precoded data is spatially combined and transmitted.<br><br>When BF is implemented at the the receiver added to BF at the transmitter provides<br><br>CHAPTER2. THEORETICAL CONCEPTS AND RELATED WORK |

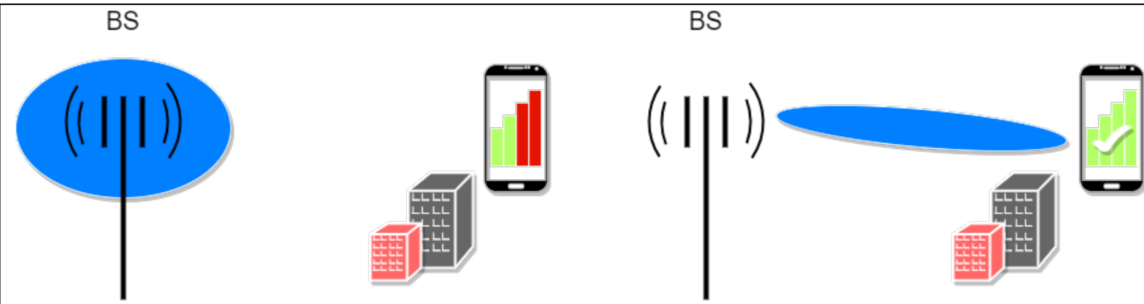


Figure 2.2.1: Compared to the BS with isotropic radiation (left) and BS that performs beamforming (right), the signal strenght of beamformed signal increases directivity towards the user which increases the received power thereby increasing the links data rate.

both array gain and diversity gain. As the number of antenna elements increases at the receiver, increases the average Signal to Noise Ratio (SNR) achieved by coherently combining all the antenna elements on the other hand diversity gain helps to increase the instantaneous SNR at the receiver by selective coherent combining of different antenna elements experiencing different fading pushing the combined SNR more concentrated towards the average SNR [11].

### 2.2.2 Spatial Multiplexing

The procedure beamforming when applied to different data streams can be spatially multiplexed in one time and frequency resource. The multipaths provided by MIMO is essentially used to improve the data rate of the UE. This can be visualised in two different scenarios as shown in figure 2.2.2.

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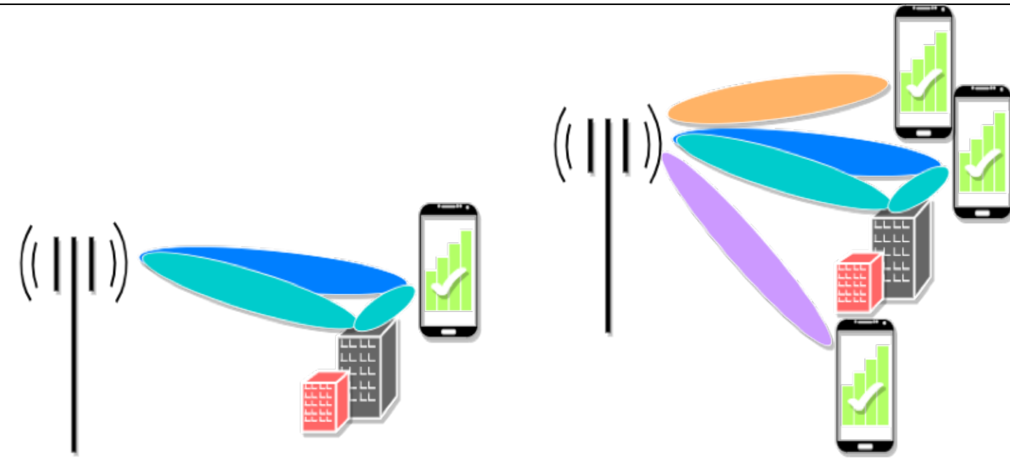
| |  Figure 2.2.2: Spatial multiplexing seen in SUMIMO(left) and MUMIMO(right). <br><br> **2.3 CSI reporting** <br><br> The BS requires a pretext before transmitting data to the respective user. This pretext is referred to the information about channel observed from the direction of the user. CSI report is considered as a feedback from UE that carries the channel information which helps in designing the precoder or choosing the optimum precoder in case of codebook based precoding. <br><br> **2.3.1 Beam Management** <br><br> CSI acquisition is done in two stages. The first stage is Beam Management (BM) where the UE measures the Reference Signal Received Power (RSRP) of the set of analog beams transmitted by the BS and reports the beam ID of the best beam to the BS [9]. NR DL measurements for BM include Synchronization Signals (SS) bursts and Channel State InformationReference Signals (CSIRS) or NR Uplink (UL) measurements for BM |

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| | include Sounding Reference Signals (SRS) as shown in figure 2.3.1. In BM based CSIRS, a set of analog beams is sent by BS to UE and the UE reports the CSI to the BS [8]. On the other hand, in BM based SRS, channel measurements are sent by the UE via a set of analog beams and received by BS. BS selects the best analog beams after measurements based on channel reciprocity where angle of arrival becomes the angle of departure of analog beams [8]. This holds, for instance, if the UE has the ability to transmit and receive with the same number of antennas as in Time Division Duplexing (TDD) [9]. However, UEs may use a different number of antennas for transmission and reception where channel reciprocity could not be met. Additionally, SRS based BM is more suitable for linear precoders as the precoder matrix requires detailed CSI whereas CSI-RS based BM is more suitable for GoB precoders. According to 5G standardization, BM in general consists of beam sweeping, beam measurement, beam determination, beam reporting , beam maintenance and beam recovery [8, 9]. These procedures are repeated to update the links periodically.<br><br>**2.3.2 PMI report**<br><br>The first stage is followed by the second stage, namely CSI acquisition report from the UE. After the NR DL or UL BM measurements, the BS assigns a subset of analog beams towards that UEs location and the UE generates the CSI report and sends the report to the BS [8]. The CSI report contains, |

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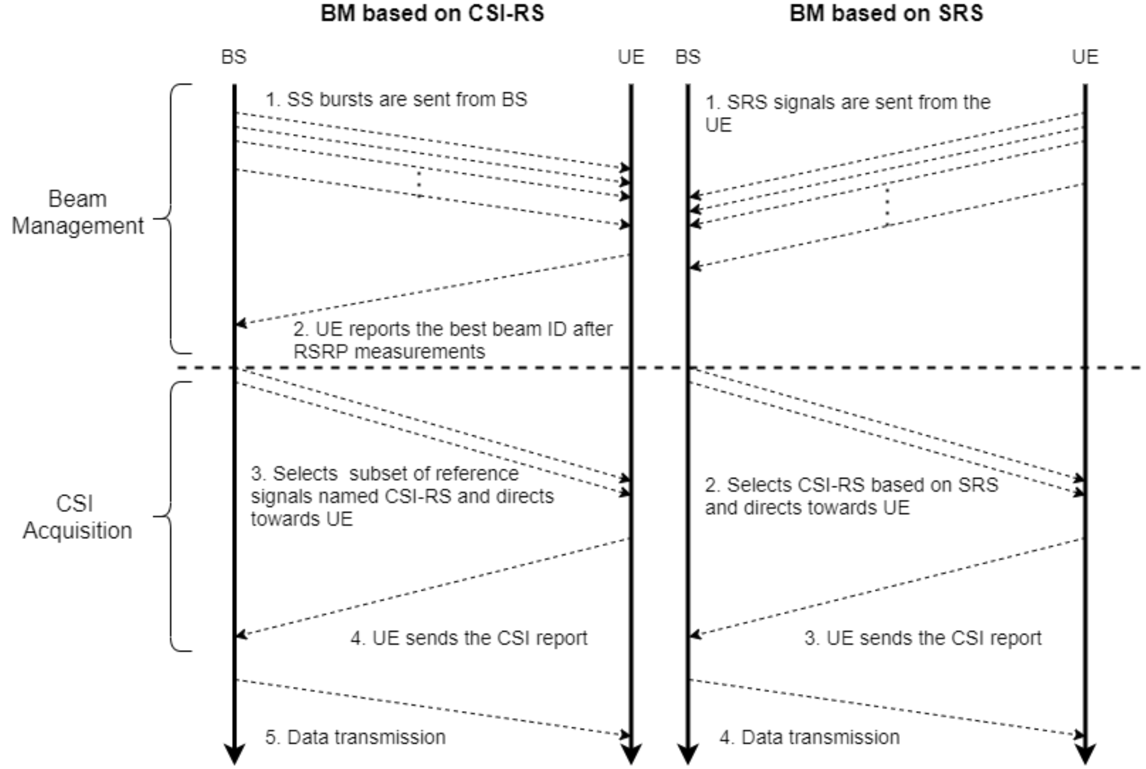
| | <br><br>Figure 2.3.1: Beam Management procedures<br><br>• *Rank Indicator (RI)*, used to indicate the preferred number of transmission layers.<br><br>• *Precoder Matrix Indicator (PMI)*, used to indicate preferred design of precoder matrix for the given rank.<br><br>• *Channel Quality Indicator (CQI)*, used to indicate the suitable channelcoding rate and modulation scheme for the given PMI. [2]. |

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| | The PMI values corresponding to the different precoder matrix is chosen from the precoder codebook defined by the standards . Despite the CSI report sent by the UE, the network can choose any precoder matrix design for data transmission. Although choosing the precoder design preferred by UE makes sense, in many cases that is not entirely possible especially in MUMIMO [10]. Therefore, NR defines two different types of CSI that differ in size and structure of the precoder matrix. *Type I CSI* (standard/low resolution) is predominantly used for SUMIMO scenarios as it relies on the UE to suppress the interference due to the different layers. This is due to the fact that the number of layers will never be larger than the number of receiver antennas. On the other hand, *Type II CSI* (high resolution) is primarily used for MUMIMO and is limited to a smaller number of layers (maximum of two). Since the number of received streams is larger than the number of receiver antennas, the interference is managed by the BS with the help of BF or precoder design [9].<br><br>See also "Chapter 3: Methodologies," which is incorporated by reference herein.<br><br>5G NR beamforming is also described in secondary sources, such as Ziao Qin and Haifan Yin, "A Review of Codebooks for CSI Feedback in 5G New Radio and Beyond," submitted, February 2023, 10.48550/arXiv.2302.09222, available online: https://arxiv.org/abs/2302.09222, also available at https://www.researchgate.net/publication/368665066_A_Review_of_Codebooks_for_CSI_Feedback_in_5G_New_Radio_and_Beyond<br><br>5G NR beamforming is also described in secondary sources, such as on the NR Cell Performance Evaluation with MIMO page on https://www.mathworks.com/help/5g/ug/nr-cell-performance-evaluation-with-mimo.html. This explains that:<br><br>**NR Cell Performance Evaluation with MIMO**<br><br>This example models a 5G New Radio (NR) cell with multiple-input multiple-output (MIMO) antenna configuration and evaluates the network performance. You can customize the scheduling strategy to leverage the MIMO capabilities and analyze the performance. This example performs downlink (DL) and uplink (UL) channel measurements using multi-port channel state information reference signals (CSI-RS) |

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| | and sounding reference signals (SRS), respectively. The gNB uses the measured channel characteristics to make MIMO scheduling decisions.<br><br>**Introduction**<br><br>MIMO improves network performance by improving the cell throughput and reliability. The example performs layer mapping and precoding to utilize MIMO in the DL and UL directions.<br><br>This example models:<br><br>• Single-codeword DL spatial multiplexing to perform multi-layer transmission. Single-codeword limits the number of transmission layers to 4.<br>• Single-codeword UL spatial multiplexing. The 3GPP specification allows only single-codeword in UL direction which limits the number of transmission layers to 4.<br>• Precoding to map the transmission layers to antenna ports. The example assumes one-to-one mapping from antenna ports to physical antennas.<br>• DL channel quality measurement by UEs based on the multi-port CSI-RS received from the gNB. The same CSI-RS configuration applies to all the UEs.<br>• UL channel quality measurement by gNB based on the multi-port SRS received from the UEs. The example does not support UL rank estimation and provides the rank to be used for estimating UL precoding matrix as a configuration parameter.<br>• DL rank indicator (RI), precoding matrix indicator (PMI), and channel quality indicator (CQI) reporting by UEs. The example supports Type-1 single-panel codebook for PMI.<br>• Free space path loss (FSPL), additive white Gaussian noise (AWGN), and clustered delay line (CDL) propagation channel model.<br><br>Nodes send the control packets (buffer status report (BSR), DL assignment, UL grants, PDSCH feedback, and CSI report) out of band, without the need of resources for transmission and assured error-free reception.<br><br>**MIMO**<br><br>The key aspects of MIMO include spatial multiplexing, precoding, channel measurement and reporting. |

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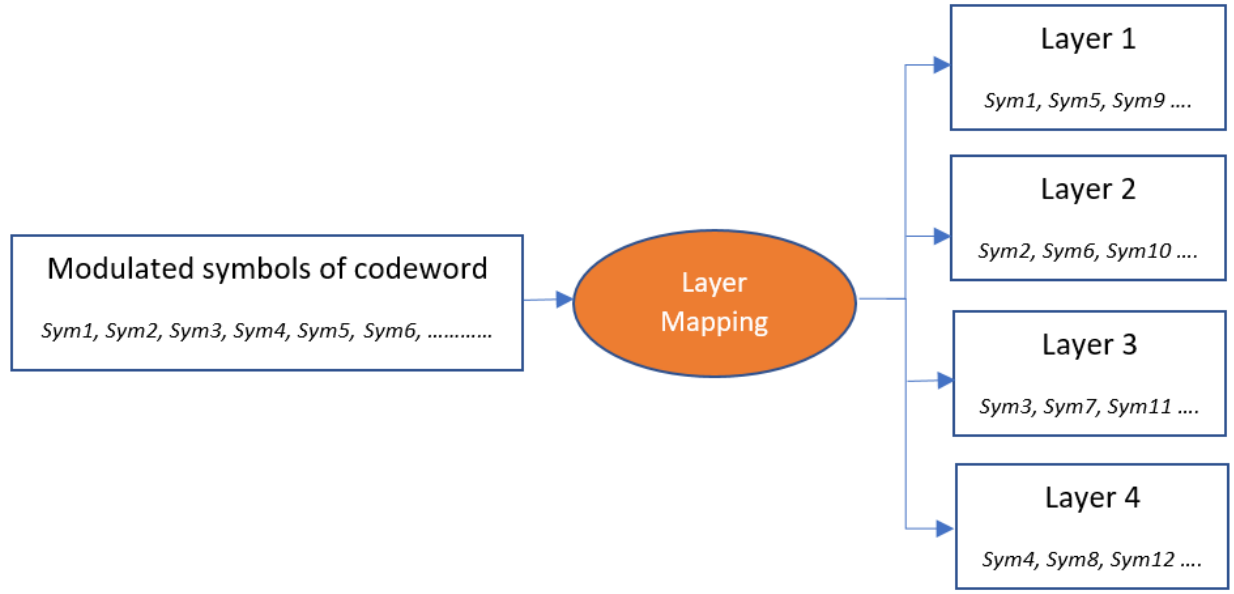
| | *Spatial multiplexing*<br><br><br>Spatial multiplexing utilizes MIMO to perform multi-layer transmission. The minimum of number of transmit and receive antennas limits the number of layers (or maximum rank). The layer mapping process maps the modulated symbols of the codeword onto different layers. It maps every $n_{\mathrm{th}}$ symbol of the codeword to $n_{\mathrm{th}}$ layer. For instance, this figure shows the mapping of a codeword onto four layers. Furthermore, in the DL direction, NR specification also allows two codewords and up to a maximum of 8 transmission layers. The example currently only supports single codeword for both DL and UL.<br><br>*Precoding* |

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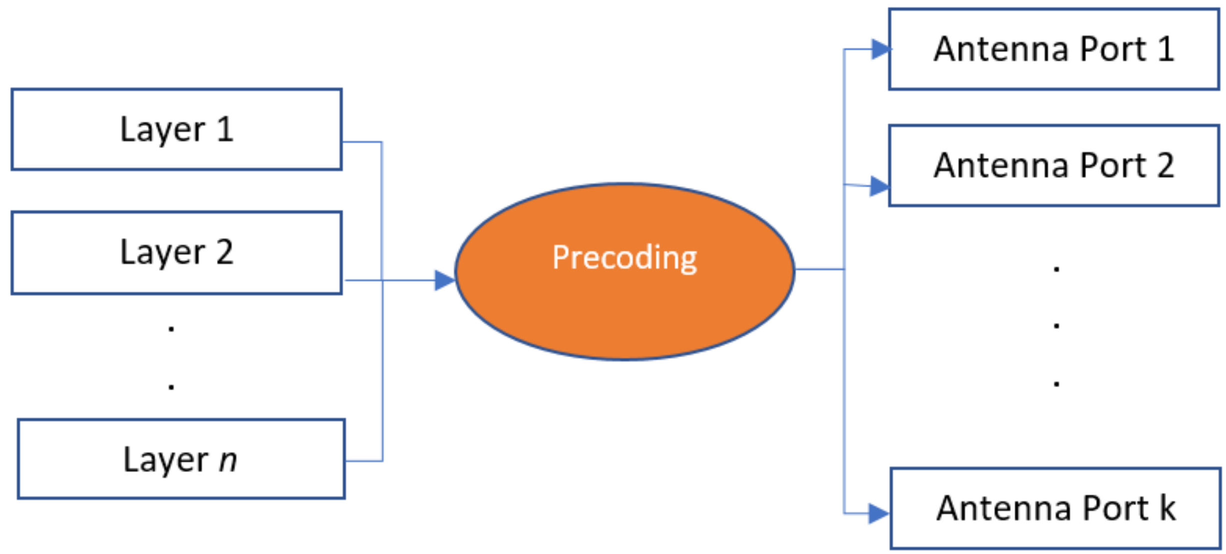


Precoding, which follows the layer mapping, maps the transmission layers to antenna ports. Precoding applies a precoding matrix to the transmission layers and outputs data streams to the antenna ports.

*Channel measurement and reporting*

It consists of DL channel measurement and reporting by the UEs and UL channel measurement by gNB.
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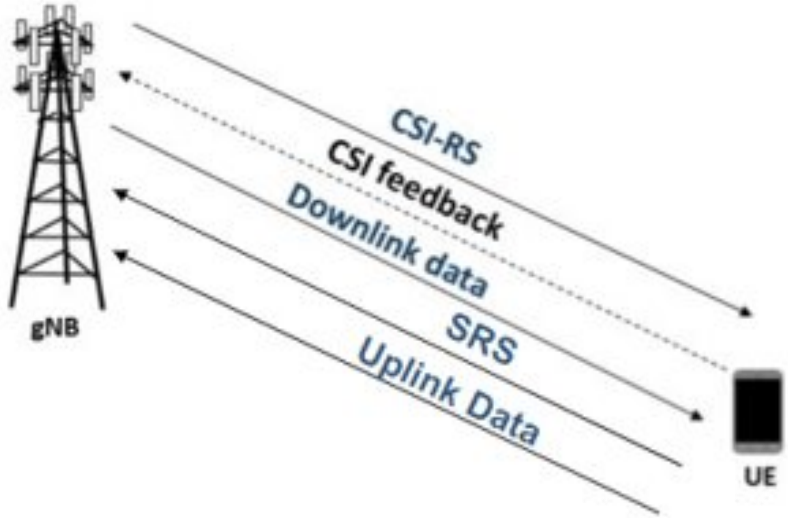
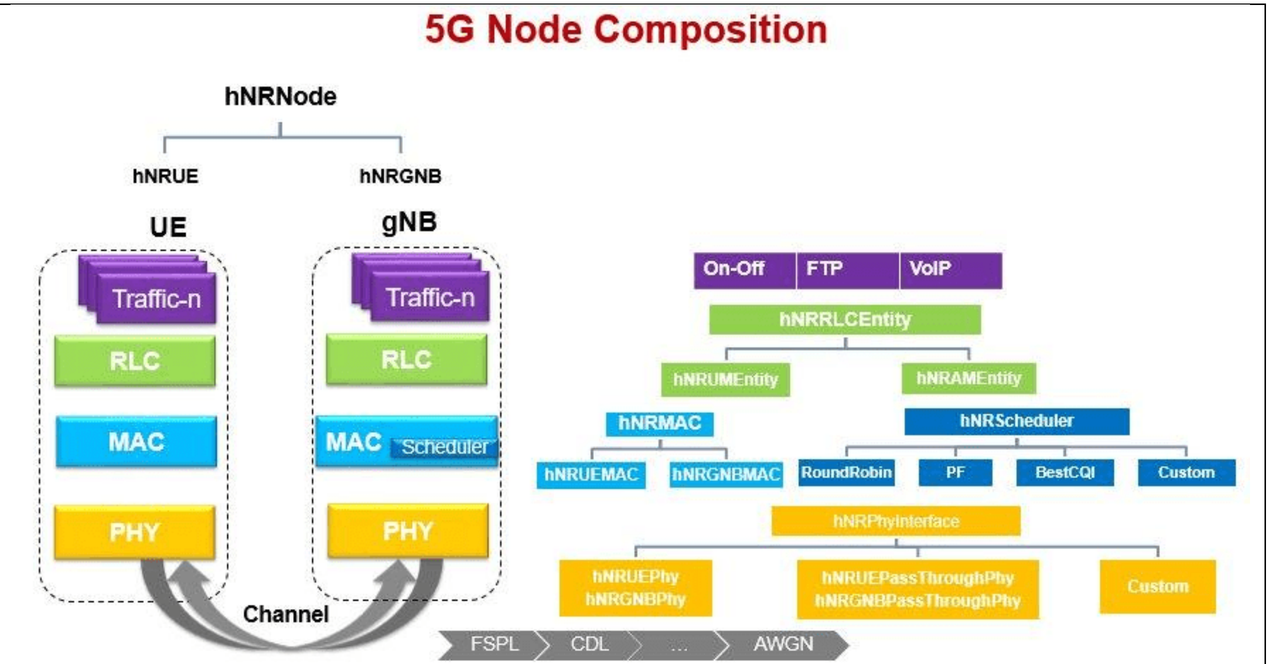
| |  <br>*DL channel measurement and reporting*<br>CSI reporting is the process by which a UE, for DL transmissions, advises a suitable number of transmission layers (rank), PMI, and CQI values to the gNB. The UE estimates these values by performing channel measurements on its configured CSI-RS resources. For more details, see the 5G NR Downlink CSI Reporting example. The gNB scheduler uses this advice to decide the number of transmission layers, precoding matrix, and modulation and coding scheme (MCS) for PDSCHs.<br>*UL channel measurement*<br>gNB uses SRS to measure UL channel characteristics in a way analogous to CSI-RS based DL channel measurements. The UL channel measurements serve as an important input to the scheduler to decide the number of transmission layers, precoding matrix and MCS for PUSCHs.<br>**NR Protocol Stack**<br>A node (gNB or UE) is a composition of NR stack layers. The helper classes hNRGNB.m and hNRUE.m create gNB and UE nodes, respectively, containing the radio link control (RLC), medium access control (MAC), and physical layer (PHY). For more details, see the NR Cell Performance Evaluation with Physical Layer Integration example. |




## Scenario Configuration

Configure simulation parameters in the `simParameters` structure.

```
rng('default'); % Reset the random number generator
simParameters = []; % Clear the simParameters variable
simParameters.NumFramesSim = 10; % Simulation time in terms of number of 10
ms frames
simParameters.SchedulingType = 0; % Set the value to 0 (slot based
scheduling) or 1 (symbol based scheduling)
```

Specify the number of UEs in the cell, assuming that UEs have sequential radio network temporary identifiers (RNTIs) from 1 to `simParameters.NumUEs`. If you change the number of UEs, ensure that the number of rows in `simParameters.UEPosition` is equal to the value of `simParameters.NumUEs`.

```
simParameters.NumUEs = 4;
% Assign position to the UEs assuming that the gNB is at (0, 0, 0). N-by-3
```

```
% matrix where 'N' is the number of UEs. Each row has (x, y, z) position of a
% UE (in meters)
simParameters.UEPosition = [300 0 0;
                            700 0 0;
                            1200 0 0;
                            3000 0 0];
% Validate the UE positions
validateattributes(simParameters.UEPosition, {'numeric'}, {'nonempty',
'real', 'nrows', simParameters.NumUEs, 'ncols', 3, 'finite'},
'simParameters.UEPosition', 'UEPosition');
```

Specify the antenna counts at the gNB and UEs.

```
simParameters.GNBTxAnts = 16;
simParameters.GNBRxAnts = 8;
simParameters.UETxAnts = 4*ones(simParameters.NumUEs, 1);
simParameters.UERxAnts = 2*ones(simParameters.NumUEs, 1);
% Validate the number of transmitter and receiver antennas at UE
validateattributes(simParameters.UETxAnts, {'numeric'}, {'nonempty',
'integer', 'nrows', simParameters.NumUEs, 'ncols', 1, 'finite'},
'simParameters.UETxAnts', 'UETxAnts')
validateattributes(simParameters.UERxAnts, {'numeric'}, {'nonempty',
'integer', 'nrows', simParameters.NumUEs, 'ncols', 1, 'finite'},
'simParameters.UERxAnts', 'UERxAnts')
```

Set the channel bandwidth to 5 MHz and the subcarrier spacing (SCS) to 15 kHz as defined in 3GPP TS 38.104 Section 5.3.2.

```
simParameters.NumRBs = 25;
simParameters.SCS = 15; % kHz
simParameters.DLCarrierFreq = 2.646e9; % Hz
simParameters.ULCarrierFreq = 2.535e9; % Hz
% The UL and DL carriers are assumed to have symmetric channel
% bandwidth
simParameters.DLBandwidth = 5e6; % Hz
simParameters.ULBandwidth = 5e6; % Hz
```

Specify the SRS configuration for each UE. The example assumes full-bandwidth SRS and transmission comb number as 4, so up to 4 UEs are frequency multiplexed in the same SRS symbol by giving different comb offset. When number of UEs are more than 4, they are assigned different SRS slot offsets.

```
simParameters.SRSSubbandSize = 4;
srsConfig = cell(1, simParameters.NumUEs);
combNumber = 4; % SRS comb number
for ueIdx = 1:simParameters.NumUEs
    % Ensure non-overlapping SRS resources when there are more than 4 UEs by
giving different offset
    srsPeriod = [10 3+floor((ueIdx-1)/4)];
    srsBandwidthMapping = nrSRSConfig.BandwidthConfigurationTable{:,2};
    csrs = find(srsBandwidthMapping <= simParameters.NumRBs, 1, 'last') - 1;
    % Set full bandwidth SRS
    srsConfig{ueIdx} = nrSRSConfig('NumSRSPorts', 4, 'SymbolStart', 13,
'SRSPeriod', srsPeriod, 'KTC', combNumber, 'KBarTC',  mod(ueIdx-1,
combNumber), 'BSRS', 0, 'CSRS', csrs);
end
simParameters.SRSConfig = srsConfig;
```

Specify the CSI-RS configuration.

```
csirs = nrCSIRSConfig('NID', 1, 'NumRB', simParameters.NumRBs, 'RowNumber',
11, 'SubcarrierLocations', [1 3 5 7], 'SymbolLocations', 0, 'CSIRSPeriod', [5
2]);
simParameters.CSIRSConfig = {csirs};
```

Specify the CSI report configuration.

```
csiReportConfig.PanelDimensions = [8 1]; % [N1 N2] as per 3GPP TS 38.214
Table 5.2.2.2.1-2
csiReportConfig.CQIMode = 'Subband'; % 'Wideband' or 'Subband'
csiReportConfig.PMIMode = 'Subband'; % 'Wideband' or 'Subband'
csiReportConfig.SubbandSize = 4; % Refer TS 38.214 Table 5.2.1.4-2 for valid
subband sizes
% Set codebook mode as 1 or 2. It is applicable only when the number of
transmission layers is 1 or 2 and
% number of CSI-RS ports is greater than 2
csiReportConfig.CodebookMode = 1;
```

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| | `simParameters.CSIReportConfig = {csiReportConfig};`<br><br>Set the UL rank to be used for precoding matrix and MCS calculation. The example does not support UL rank estimation. For each UE, set a number less than or equal to the minimum of UE's transmit antennas and gNB's receive antennas.<br><br>`simParameters.ULRankIndicator = 2*ones(1, simParameters.NumUEs);`<br><br>The foregoing descriptions focus on, *inter alia*, a base station sending CSI-RS to the UE and then receiving CSI feedback from the UE, which the base station analyzes in determining the DL precoding matrix and transmission layers, as well as a base station receiving SRS from the UE, which the base station analyzes in determining the transmission layers, precoding matrix, and MCS for uplink transmissions using PUSCH and at least in the case of TDD, 5G NR base station can also analyze received SRS to determine transmission layers and precoding for downlink transmissions. 5G NR base station can analyze received CSI feedback and SRS from UE to perform channel estimation and to determine forward path pre-equalization modification for the transmission layers and precoding.<br><br>See also, e.g., 5G NR Downlink CSI Reporting page on https://www.mathworks.com/help/5g/ug/5g-nr-downlink-csi-reporting.html. This explains that, e.g., the UE computes CSI feedback for the base station, which the base station analyzes to determine a set of weighting values configured to be used to pre-code for MIMO beamforming to the UE using type I or type II codebooks:<br><br>This example shows how to compute downlink channel state information (CSI) parameters such as the channel quality indicator (CQI), precoding matrix indicator (PMI) for multiple input multiple output (MIMO) scenarios, and rank indicator (RI), as defined in TS 38.214 Section 5.2.2, over a tapped delay line (TDL) channel. The example supports CSI parameter computation considering type I single-panel, type I multi-panel, and type II codebooks.<br><br>**Introduction**<br><br>CSI parameters are the quantities related to the state of a channel. The user equipment (UE) reports CSI parameters to the access network node (gNB) as feedback. The CSI feedback includes several parameters, such as the CQI, the PMI with different codebook sets, and the rank indicator (RI). The UE uses the channel state information reference signal (CSI-RS) to measure the CSI feedback. Upon receiving the CSI parameters, the gNB schedules downlink data transmissions (such as modulation scheme, code rate, number of transmission layers, and MIMO precoding) accordingly. This figure shows |

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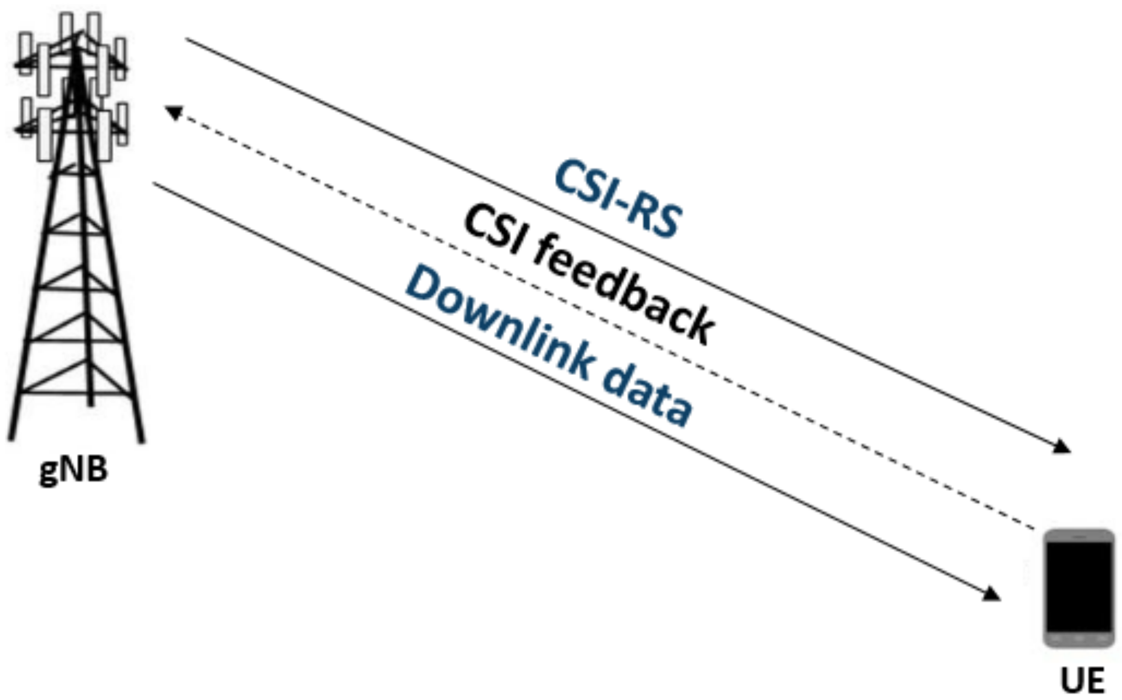
| | an overview of CSI-RS transmission, CSI computation and feedback, and the transmission of downlink data that is scheduled based on the CSI parameters.<br><br><br>See also, e.g., https://www.mathworks.com/help/lte/ug/uplink-waveform-modeling-using-srs-and-pucch.html<br>https://www.mathworks.com/help/5g/ug/nr-uplink-channel-state-information-estimation-using-srs.html<br>https://www.mathworks.com/help/5g/ug/nr-sounding-reference-signals.html |

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| | According to the 5G NR Standard, the parameter “maxNrofSSBs” in 3GPP TS 38.331 indicates the maximum number of beams supported by the base station. For example, a base station can support up to 4 beams under 3 GHz, up to 8 beams for 3-6 GHz, and up to 64 beams for 6-52.6 GHz. The maximum number of SSBs, with one beam paired to each SSB, depends on the frequency supported and on the subcarrier spacing (SCS) used. The maximum number of supported beams is signaled via Radio Resource Control as specified by 3GPP TS 38.331 V17.2.0 (2022-09), Section 6.4 (RRC multiplicity and type constraint values).<br>`maxNrofSSBs-r16 INTEGER ::= 64 -- Maximum number of SSB resources in a resource set.`<br>Furthermore, the number of beams for each frequency band, is specified in 3GPP TS 38.213 V17.4.0 (2022-12), section 4.1 (Cell search) as follows:<br>--<br>4.1 Cell search<br>Cell search is the procedure for a UE to acquire time and frequency synchronization with a cell and to detect the physical layer Cell ID of the cell.<br>A UE receives the following synchronization signals (SS) in order to perform cell search: the primary synchronization signal (PSS) and secondary synchronization signal (SSS) as defined in [4, TS 38.211].<br>A UE assumes that reception occasions of a physical broadcast channel (PBCH), PSS, and SSS are in consecutive symbols, as defined in [4, TS 38.211], and form a SS/PBCH block. The UE assumes that SSS, PBCH DM-RS, and PBCH data have same EPRE. The UE may assume that the ratio of PSS EPRE to SSS EPRE in a SS/PBCH block is either 0 dB or 3 dB. If the UE has not been provided dedicated higher layer parameters, the UE may assume that the ratio of PDCCH DMRS EPRE to SSS EPRE is within -8 dB and 8 dB when the UE monitors PDCCHs for a DCI format 1_0 with CRC scrambled by SI-RNTI, P-RNTI, or RA-RNTI, or for a DCI format 2_7.<br>For a half frame with SS/PBCH blocks, the first symbol indexes for candidate SS/PBCH blocks are determined according to the SCS of SS/PBCH blocks as follows, where index 0 corresponds to the first symbol of the first slot in a half-frame.<br>- Case A - 15 kHz SCS: the first symbols of the candidate SS/PBCH blocks have indexes of $\{2,8\} + 14 \cdot n$. |

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| | - For operation without shared spectrum channel access:<br>- For carrier frequencies smaller than or equal to 3 GHz, $n = 0,1$.<br>- For carrier frequencies within FR1 larger than 3 GHz, $n = 0,1,2,3$.<br>- For operation with shared spectrum channel access, as described in [15, TS 37.213], $n = 0, 1, 2, 3, 4$.<br>- Case B - 30 kHz SCS: the first symbols of the candidate SS/PBCH blocks have indexes $\{4,8,16,20\} + 28 \cdot n$. For carrier frequencies smaller than or equal to 3 GHz, $n = 0$. For carrier frequencies within FR1 larger than 3 GHz, $n = 0,1$.<br>- Case C - 30 kHz SCS: the first symbols of the candidate SS/PBCH blocks have indexes $\{2,8\} + 14 \cdot n$.<br>- For operation without shared spectrum channel access<br>- For paired spectrum operation<br>- For carrier frequencies smaller than or equal to 3 GHz, $n = 0,1$. For carrier frequencies within FR1 larger than 3 GHz, $n = 0,1,2,3$.<br>- For unpaired spectrum operation<br>- For carrier frequencies smaller than 1.88 GHz, $n = 0,1$. For carrier frequencies within FR1 equal to or larger than 1.88 GHz, $n = 0,1,2,3$.<br>- For operation with shared spectrum channel access, $n = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9$.<br>- Case D - 120 kHz SCS: the first symbols of the candidate SS/PBCH blocks have indexes $\{4,8,16,20\} + 28 \cdot n$. For carrier frequencies within FR2, $n = 0, 1, 2, 3, 5, 6, 7, 8, 10, 11, 12, 13, 15, 16, 17, 18$.<br>- Case E - 240 kHz SCS: the first symbols of the candidate SS/PBCH blocks have indexes $\{8,12,16,20,32,36,40,44\} + 56 \cdot n$. For carrier frequencies within FR2-1, $n = 0, 1, 2, 3, 5, 6, 7, 8$.<br>- Case F – 480 kHz SCS: the first symbols of the candidate SS/PBCH blocks have indexes $\{2, 9\} + 14 \cdot n$. For carrier frequencies within FR2-2, $n = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31$.<br>- Case G – 960 kHz SCS: the first symbols of the candidate SS/PBCH blocks have indexes $\{2, 9\} + 14 \cdot n$. For carrier frequencies within FR2-2, $n = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31$. |

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| | … <br><br> The candidate SS/PBCH blocks in a half frame are indexed in an ascending order in time from 0 to $\overline{L}_{max} - 1$, where $\overline{L}_{max}$ is determined according to SS/PBCH block patterns for Cases A through G. $L_{max}$ is a maximum number of SS/PBCH block indexes in a cell, and the maximum number of transmitted SS/PBCH blocks within a half frame is $L_{max}$. <br><br> - For operation without shared spectrum channel access in FR1 and FR2, and for operation with shared spectrum channel access in FR2-2, $L_{max} = \overline{L}_{max}$ <br><br> - For operation with shared spectrum channel access in FR1, $L_{max} = 8$ for $\overline{L}_{max} = 10$ and 15 kHz SCS of SS/PBCH blocks and for $\overline{L}_{max} = 20$ and 30 kHz SCS of SS/PBCH blocks <br><br> For $\overline{L}_{max} = 4$, a UE determines the 2 LSB bits of a candidate SS/PBCH block index per half frame from a one-to-one mapping with an index of the DM-RS sequence transmitted in the PBCH as described in [4, TS 38.211]. <br><br> For $\overline{L}_{max} > 4$, a UE determines the 3 LSB bits of a candidate SS/PBCH block index per half frame from a one-to-one mapping with an index of the DM-RS sequence transmitted in the PBCH as described in [4, TS 38.211] <br><br> - for $\overline{L}_{max} = 10$, the UE determines the 1 MSB bit of the candidate SS/PBCH block index from PBCH payload bit $\bar{a}_{\bar{A}+7}$ as described in [5, TS 38.212] <br><br> - for $\overline{L}_{max} = 20$, the UE determines the 2 MSB bits of the candidate SS/PBCH block index from PBCH payload bits $\bar{a}_{\bar{A}+6}, \bar{a}_{\bar{A}+7}$ as described in [5, TS 38.212] <br><br> - for $\overline{L}_{max} = 64$, the UE determines the 3 MSB bits of the candidate SS/PBCH block index from PBCH payload bits $\bar{a}_{\bar{A}+5}, \bar{a}_{\bar{A}+6}, \bar{a}_{\bar{A}+7}$ as described in [5, TS 38.212] <br><br> -- <br><br> 3GPP 5G NR Release 17 provides enhancements to massive MIMO multi-beam operations. The base station will adapt one or more of the beams of an antenna array to facilitate coverage of the mobile wireless device: |

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| | **Beam Level Mobility** does not require explicit RRC signalling to be triggered. Beam level mobility can be within a cell, or between cells, the latter is referred to as inter-cell beam management (ICBM). For ICBM, a UE can receive or transmit UE dedicated channels/signals via a TRP associated with a PCI different from the PCI of a serving cell, while non-UE-dedicated channels/signals can only be received via a TRP associated with a PCI of the serving cell. The gNB provides via RRC signalling the UE with measurement configuration containing configurations of SSB/CSI resources and resource sets, reports and trigger states for triggering channel and interference measurements and reports. In case o ICBM, a measurement configuration includes SSB resources associated with PCIs different from the PCI of a serving cell. Beam Level Mobility is then dealt with at lower layers by means of physical layer and MAC layer control signalling, and RRC is not required to know which beam is being used at a given point in time.<br><br>SSB-based Beam Level Mobility is based on the SSB associated to the initial DL BWP and can only be configured for the initial DL BWPs and for DL BWPs containing the SSB associated to the initial DL BWP. For other DL BWPs, Beam Level Mobility can only be performed based on CSI-RS.<br><br>(3GPP TS 38.300 v17.2.0, § 9.2.3.1)<br><br>Beam Level Mobility, and other uses cases for relying on uplink transmissions from UE for beam-forming, has been supported in 5G NR since at least 3GPP 5G NR Release 15. See 3GPP TS 38.300 v15.8.0 at § 9.2.3.1. Beam measurement, reporting, and consolidation/selection is described in part at 3GPP TS 38.300 § 9.2.4. The base station can also refine or adjust beamforming and MIMO precoding based on UE measurement feedback or channel estimation, such as of this type:<br><br>**9.2.4 Measurements**<br><br>In RRC_CONNECTED, the UE measures multiple beams (at least one) of a cell and the measurements results (power values) are averaged to derive the cell quality. In doing so, the UE is configured to consider a subset of the detected beams. Filtering takes place at two different levels: at the physical layer to derive beam quality and then at RRC level to derive cell quality from multiple beams. Cell quality from beam measurements is derived in the same way for the serving cell(s) and for the non-serving cell(s). Measurement reports may contain the measurement results of the *X* best beams if the UE is configured to do so by the gNB.<br><br>The corresponding high-level measurement model is described below: |

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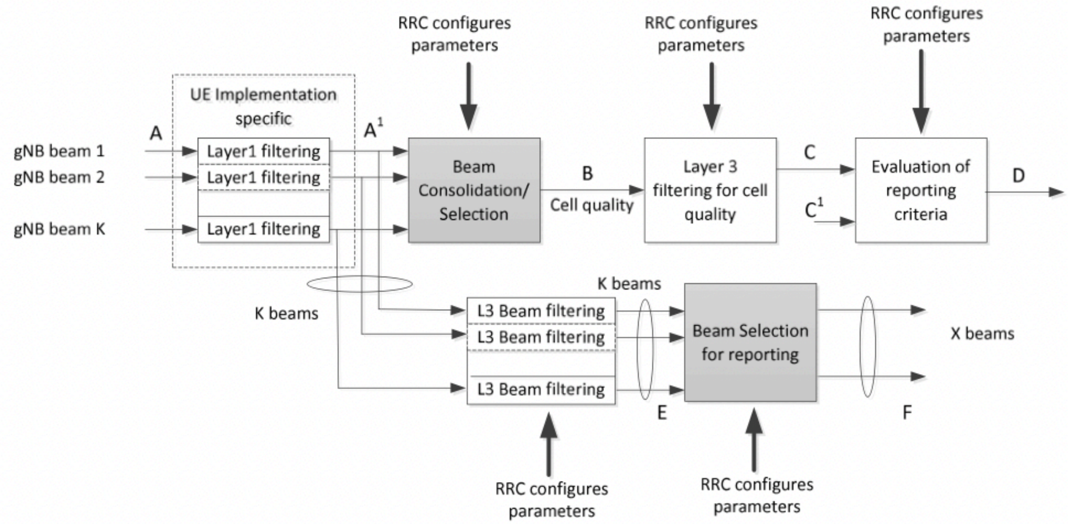
| | <br>**Figure 9.2.4-1: Measurement Model**<br><br>NOTE: K beams correspond to the measurements on SSB or CSI-RS resources configured for L3 mobility by gNB and detected by UE at L1.<br><br>- **A**: measurements (beam specific samples) internal to the physical layer.<br><br>- **Layer 1 filtering**: internal layer 1 filtering of the inputs measured at point A. Exact filtering is implementation dependent. How the measurements are actually executed in the physical layer by an implementation (inputs A and Layer 1 filtering) in not constrained by the standard.<br><br>- **A$^1$**: measurements (i.e. beam specific measurements) reported by layer 1 to layer 3 after layer 1 filtering.<br><br>- **Beam Consolidation/Selection**: beam specific measurements are consolidated to derive cell quality. The behaviour of the Beam consolidation/selection is standardised and the configuration of this module is provided by RRC signalling. Reporting period at B equals one measurement period at A$^1$.<br><br>- **B**: a measurement (i.e. cell quality) derived from beam-specific measurements reported to layer 3 after beam consolidation/selection.<br><br>See, e.g., |

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| | 3GPP TS 38.300 v15.3.1 Release 15 (ETSI TS 138 300 V15.3.1 (2018-10)), Section 5.5<br><br>**5.5 Transport Channels**<br><br>The physical layer offers information transfer services to MAC and higher layers. The physical layer transport services are described by *how* and with what characteristics data are transferred over the radio interface. An adequate term for this is "Transport Channel". This should be clearly separated from the classification of *what* is transported, which relates to the concept of logical channels at MAC sublayer.<br><br>Downlink transport channel types are:<br><br>1. **Broadcast Channel (BCH)** characterised by:<br>o - fixed, pre-defined transport format;<br>o - requirement to be broadcast in the entire coverage area of the cell, either as a single message or by beamforming different BCH instances.<br>2. **Downlink Shared Channel (DL-SCH)** characterised by:<br>o - support for HARQ;<br>o - support for dynamic link adaptation by varying the modulation, coding and transmit power;<br>o - possibility to be broadcast in the entire cell;<br>o - possibility to use beamforming;<br>o - support for both dynamic and semi-static resource allocation;<br>o - support for UE discontinuous reception (DRX) to enable UE power saving;<br>3. **Paging Channel (PCH)** characterised by:<br>o - support for UE discontinuous reception (DRX) to enable UE power saving (DRX cycle is indicated by the network to the UE);<br>o - requirement to be broadcast in the entire coverage area of the cell, either as a single message or by beamforming different BCH instances;<br>o - mapped to physical resources which can be used dynamically also for traffic/other control channels.<br><br>*See, e.g.* the following references:<br><br>3GPP TS 38.300 v15.3.1 Release 15 (ETSI TS 138 300 V15.3.1 (2018-10)), Sections 5.5, 9.2.3, 9.2.4, 9.2.6, 9.2.8; |

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| | 3GPP TS 38.331 v15.3.0 Release 15 (ETSI TS 138 331 V15.3.0 (2018-10), Section 6.3.2 at *BeamFailureRecoveryConfig*, *PUSCH-PowerControl*, *RACH-ConfigDedicated*, *RACH-ConfigDedicated*, *RACH-ConfigGeneric*, *RadioLinkMonitoringConfig, ReportConfigNR, ServingCellConfig, SRS-Config, MIMO-Layers, MIMO-ParametersPerBand,* among other IE;<br><br>3GPP TS 38.321 v15.3.0 Release 15 (ETSI TS 138 321 V15.3.0 (2018-09), Section 5.1<br><br>3GPP TS 38.213 v15.3.0 Release 15 (ETSI TS 138 213 V15.3.0 (2018-10), Section 6 (Link recovery procedures), Section 7.1.1 (PUSCH beam indication provides indication of the set to be used for a particular PUSCH transmission), Section 7.3 (Sounding reference signals); *see also* 3GPP TS 38.331 v15.3.0 Release 15, Section 6.3.2 at *PUSCH-PowerControl*.<br><br>3GPP TS 38.214 v16.2 Release 16 (2020) Section 5.2 (UE procedure for reporting channel state information (CSI)), Section 6 (Physical uplink shared channel related procedure)<br><br>From 3GPP TS 38.300 v15.3.1 Release 15:<br><br>**9.2.3 Mobility in RRC_CONNECTED**<br><br>**9.2.3.1 Overview**<br><br>Network controlled mobility applies to UEs in RRC_CONNECTED and is categorized into two types of mobility: cell level mobility and beam level mobility.<br><br>**Cell Level Mobility** requires explicit RRC signalling to be triggered, i.e. handover. For inter-gNB handover, the signalling procedures consist of at least the following elemental components illustrated in Figure 9.2.3.1-1: |

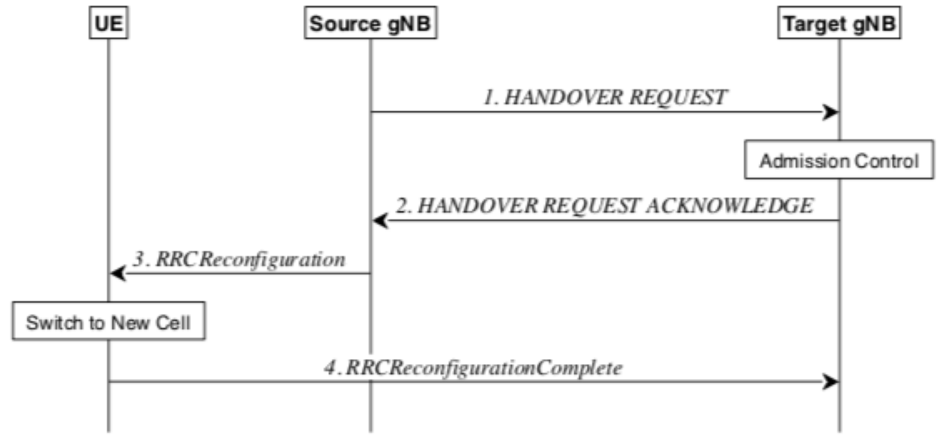


**Figure 9.2.3.1-1: Inter-gNB handover procedures**

1. The source gNB initiates handover and issues a Handover Request over the Xn interface.
2. The target gNB performs admission control and provides the RRC configuration as part of the Handover Acknowledgement.
3. The source gNB provides the RRC configuration to the UE in the Handover Command. The Handover Command message includes at least cell ID and all information required to access the target cell so that the UE can access the target cell without reading system information. For some cases, the information required for contention-based and contention-free random access can be included in the Handover Command message. The access information to the target cell may include beam specific information, if any.
4. The UE moves the RRC connection to the target gNB and replies the Handover Complete.

NOTE: User Data can also be sent in step 4 if the grant allows.

The handover mechanism triggered by RRC requires the UE at least to reset the MAC entity and re-establish RLC. RRC managed handovers with and without PDCP entity re-establishment are both supported. For DRBs using RLC AM mode, PDCP can either be re-established together with a security key change or initiate a data recovery procedure without a key change. For DRBs using RLC UM mode and for SRBs, PDCP can either be re-established together with a security key change or remain as it is without a key change.

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| | Data forwarding, in-sequence delivery and duplication avoidance at handover can be guaranteed when the target gNB uses the same DRB configuration as the source gNB.<br><br>Timer based handover failure procedure is supported in NR. RRC connection re-establishment procedure is used for recovering from handover failure.<br><br>**Beam Level Mobility** does not require explicit RRC signalling to be triggered. The gNB provides via RRC signalling the UE with measurement configuration containing configurations of SSB/CSI resources and resource sets, reports and trigger states for triggering channel and interference measurements and reports. Beam Level Mobility is then dealt with at lower layers by means of physical layer and MAC layer control signalling, and RRC is not required to know which beam is being used at a given point in time.<br><br>**9.2.4 Measurements**<br><br>In RRC_CONNECTED, the UE measures multiple beams (at least one) of a cell and the measurements results (power values) are averaged to derive the cell quality. In doing so, the UE is configured to consider a subset of the detected beams. Filtering takes place at two different levels: at the physical layer to derive beam quality and then at RRC level to derive cell quality from multiple beams. Cell quality from beam measurements is derived in the same way for the serving cell(s) and for the non-serving cell(s). Measurement reports may contain the measurement results of the *X* best beams if the UE is configured to do so by the gNB.<br><br>The corresponding high-level measurement model is described below: |

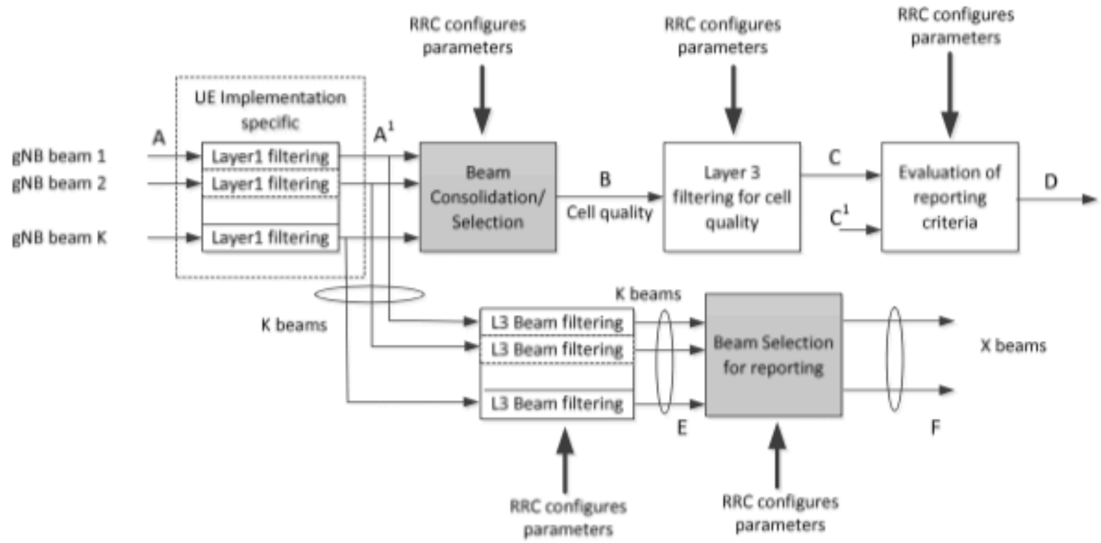


**Figure 9.2.4-1: Measurement Model**

NOTE: K beams correspond to the measurements on SSB or CSI-RS resources configured for L3 mobility by gNB and detected by UE at L1.

- \- **A**: measurements (beam specific samples) internal to the physical layer.
- \- **Layer 1 filtering**: internal layer 1 filtering of the inputs measured at point A. Exact filtering is implementation dependent. How the measurements are actually executed in the physical layer by an implementation (inputs A and Layer 1 filtering) in not constrained by the standard.
- \- **$A^1$**: measurements (i.e. beam specific measurements) reported by layer 1 to layer 3 after layer 1 filtering.
- **- Beam Consolidation/Selection**: beam specific measurements are consolidated to derive cell quality. The behaviour of the Beam consolidation/selection is standardised and the configuration of this module is provided by RRC signalling. Reporting period at B equals one measurement period at $A^1$.
- **- B**: a measurement (i.e. cell quality) derived from beam-specific measurements reported to layer 3 after beam consolidation/selection.
- \- **Layer 3 filtering for cell quality**: filtering performed on the measurements provided at point B. The behaviour of the Layer 3 filters is standardised and the configuration of the layer 3 filters is provided by RRC signalling. Filtering reporting period at C equals one measurement period at B.

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| | • - **C**: a measurement after processing in the layer 3 filter. The reporting rate is identical to the reporting rate at point B. This measurement is used as input for one or more evaluation of reporting criteria.<br>• - **Evaluation of reporting criteria**: checks whether actual measurement reporting is necessary at point D. The evaluation can be based on more than one flow of measurements at reference point C e.g. to compare between different measurements. This is illustrated by input C and $C^1$. The UE shall evaluate the reporting criteria at least every time a new measurement result is reported at point C, $C^1$. The reporting criteria are standardised and the configuration is provided by RRC signalling (UE measurements).<br>• - **D**: measurement report information (message) sent on the radio interface.<br>• - **L3 Beam filtering**: filtering performed on the measurements (i.e. beam specific measurements) provided at point $A^1$. The behaviour of the beam filters is standardised and the configuration of the beam filters is provided by RRC signalling. Filtering reporting period at E equals one measurement period at $A^1$.<br>• - **E**: a measurement (i.e. beam-specific measurement) after processing in the beam filter. The reporting rate is identical to the reporting rate at point $A^1$. This measurement is used as input for selecting the X measurements to be reported.<br><br>• - **Beam Selection for beam reporting**: selects the X measurements from the measurements provided at point E. The behaviour of the beam selection is standardised and the configuration of this module is provided by RRC signalling.<br>• - **F**: beam measurement information included in measurement report (sent) on the radio interface.<br><br>Layer 1 filtering introduces a certain level of measurement averaging. How and when the UE exactly performs the required measurements is implementation specific to the point that the output at B fulfils the performance requirements set in 3GPP TS 38.133 [13]. Layer 3 filtering for cell quality and related parameters used are specified in 3GPP TS 38.331 [12] and do not introduce any delay in the sample availability between B and C. Measurement at point C, $C^1$ is the input used in the event evaluation. L3 Beam filtering and related parameters used are specified in 3GPP TS 38.331 [12] and do not introduce any delay in the sample availability between E and F.<br><br>Measurement reports are characterized by the following:<br><br>• - Measurement reports include the measurement identity of the associated measurement configuration that triggered the reporting;<br>• - Cell and beam measurement quantities to be included in measurement reports are configured by the network;<br>• - The number of non-serving cells to be reported can be limited through configuration by the network;<br>• - Cells belonging to a blacklist configured by the network are not used in event evaluation and reporting, and conversely when a whitelist is configured by the network, only the cells belonging to the whitelist are used in event evaluation and reporting; |

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| | • - Beam measurements to be included in measurement reports are configured by the network (beam identifier only, measurement result and beam identifier, or no beam reporting).<br><br>**9.2.6 Random Access Procedure**<br><br>The random access procedure is triggered by a number of events, for instance:<br><br>• - Initial access from RRC_IDLE;<br>• - RRC Connection Re-establishment procedure;<br>• - Handover;<br>• - DL or UL data arrival during RRC_CONNECTED when UL synchronisation status is "non-synchronised";<br>• - Transition from RRC_INACTIVE;<br>• - To establish time alignment at SCell addition;<br>• - Request for Other SI (see subclause 7.3);<br>• - Beam failure recovery.<br><br>**9.2.8 Beam failure detection and recovery**<br><br>For beam failure detection, the gNB configures the UE with beam failure detection reference signals and the UE declares beam failure when the number of beam failure instance indications from the physical layer reaches a configured threshold within a configured period.<br><br>After beam failure is detected, the UE:<br><br>• - triggers beam failure recovery by initiating a Random Access procedure on the PCell;<br>• - selects a suitable beam to perform beam failure recovery (if the gNB has provided dedicated Random Access resources for certain beams, those will be prioritized by the UE).<br><br>Upon completion of the Random Access procedure, beam failure recovery is considered complete.<br><br>—<br><br><u>From 3GPP TS 38.331 v15.3.0 Release 15</u>: |

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| | ## 5.5 Measurements<br><br>### 5.5.1 Introduction<br><br>The network may configure an RRC_CONNECTED UE to perform measurements and report them in accordance with the measurement configuration. The measurement configuration is provided by means of dedicated signalling i.e. using the *RRCReconfiguration.*<br><br>The network may configure the UE to perform the following types of measurements:<br><br>• - NR measurements;<br>• - Inter-RAT measurements of E-UTRA frequencies.<br><br>The network may configure the UE to report the following measurement information based on SS/PBCH block(s):<br><br>• - Measurement results per SS/PBCH block;<br>• - Measurement results per cell based on SS/PBCH block(s);<br>• - SS/PBCH block(s) indexes.<br><br>The network may configure the UE to report the following measurement information based on CSI-RS resources:<br><br>• - Measurement results per CSI-RS resource;<br>• - Measurement results per cell based on CSI-RS resource(s);<br>• - CSI-RS resource measurement identifiers.<br><br>The measurement configuration includes the following parameters:<br><br>1. **Measurement objects:** A list of objects on which the UE shall perform the measurements.<br>- For intra-frequency and inter-frequency measurements a measurement object indicates the frequency/time location and subcarrier spacing of reference signals to be measured. Associated with this measurement object, the network may configure a list of cell specific offsets, a list of 'blacklisted' cells and a list of 'whitelisted' cells. Blacklisted cells are not applicable in event evaluation or measurement reporting. Whitelisted cells are the only ones applicable in event evaluation or measurement reporting.<br>- The *measObjectId*of the MO which corresponds to each serving cell is indicated by *servingCellMO* within the serving cell configuration. |

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| | - For inter-RAT E-UTRA measurements a measurement object is a single EUTRA carrier frequency. Associated with this E-UTRA carrier frequency, the network can configure a list of cell specific offsets, a list of 'blacklisted' cells and a list of 'whitelisted' cells. Blacklisted cells are not applicable in event evaluation or measurement reporting. Whitelisted cells are the only ones applicable in event evaluation or measurement reporting.<br>2. **Reporting configurations:** A list of reporting configurations where there can be one or multiple reporting configurations per measurement object. Each reporting configuration consists of the following:<br>- Reporting criterion: The criterion that triggers the UE to send a measurement report. This can either be periodical or a single event description.<br>- RS type: The RS that the UE uses for beam and cell measurement results (SS/PBCH block or CSI-RS).<br>- Reporting format: The quantities per cell and per beam that the UE includes in the measurement report (e.g. RSRP) and other associated information such as the maximum number of cells and the maximum number beams per cell to report.<br>3. **Measurement identities:** A list of measurement identities where each measurement identity links one measurement object with one reporting configuration. By configuring multiple measurement identities, it is possible to link more than one measurement object to the same reporting configuration, as well as to link more than one reporting configuration to the same measurement object. The measurement identity is also included in the measurement report that triggered the reporting, serving as a reference to the network.<br><br>4. **Quantity configurations:** The quantity configuration defines the measurement filtering configuration used for all event evaluation and related reporting, and for periodical reporting of that measurement. For NR measurements, the network may configure up to 2 quantity configurations with a reference in the NR measurement object to the configuration that is to be used. In each configuration, different filter coefficients can be configured for different measurement quantities, for different RS types, and for measurements per cell and per beam.<br>**5.** **Measurement gaps:** Periods that the UE may use to perform measurements, i.e. no (UL, DL) transmissions are scheduled.<br><br>A UE in RRC_CONNECTED maintains a measurement object list, a reporting configuration list, and a measurement identities list according to signalling and procedures in this specification. The measurement object list possibly includes NR measurement object(s) and inter-RAT objects. Similarly, the reporting configuration list includes NR and inter- RAT reporting configurations. Any measurement object can be linked to any reporting configuration of the same RAT type. Some reporting configurations may not be linked to a measurement object. Likewise, some measurement objects may not be linked to a reporting configuration.<br><br>The measurement procedures distinguish the following types of cells:<br><br>1. The NR serving cell(s) - these are the SpCell and one or more SCells. |

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| | 2. Listed cells - these are cells listed within the measurement object(s).<br>3. Detected cells - these are cells that are not listed within the measurement object(s) but are detected by the UE on the SSB frequency(ies) and subcarrier spacing(s) indicated by the measurement object(s).<br><br>For NR measurement object(s), the UE measures and reports on the serving cell(s), listed cells and/or detected cells. For inter-RAT measurements object(s) of E-UTRA, the UE measures and reports on listed cells and detected cells.<br><br>Whenever the procedural specification, other than contained in sub-clause 5.5.2, refers to a field it concerns a field included in the *VarMeasConfig* unless explicitly stated otherwise i.e. only the measurement configuration procedure covers the direct UE action related to the received *measConfig*.<br><br>…<br><br>**5.5.3 Performing measurements**<br><br>**5.5.3.1 General**<br><br>An RRC_CONNECTED UE shall derive cell measurement results by measuring one or multiple beams associated per cell as configured by the network, as described in 5.5.3.3. For all cell measurement results in RRC_CONNECTED the UE applies the layer 3 filtering as specified in 5.5.3.2, before using the measured results for evaluation of reporting criteria and measurement reporting. For cell measurements, the network can configure RSRP, RSRQ or SINR as trigger quantity. Reporting quantities can be the same as trigger quantity or combinations of quantities (i.e. RSRP and RSRQ; RSRP and SINR; RSRQ and SINR; RSRP, RSRQ and SINR).<br><br>The network may also configure the UE to report measurement information per beam (which can either be measurement results per beam with respective beam identifier(s) or only beam identifier(s)), derived as described in 5.5.3.3a. If beam measurement information is configured to be included in measurement reports, the UE applies the layer 3 beam filtering as specified in 5.5.3.2. On the other hand, the exact layer 1 filtering of beam measurements used to derive cell measurement results is implementation dependent.<br><br>The UE shall:<br><br>1> whenever the UE has a *measConfig*, perform RSRP and RSRQ measurements for each serving cell for which *servingCellMO* is configured as follows: |

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| | 2> if at least one *measId* included in the *measIdList* within *VarMeasConfig* contains an *rsType* set to *ssb*:<br><br>3> if at least one *measId* included in the *measIdList* within *VarMeasConfig* contains a *reportQuantityRsIndexes* and *maxNrofRSIndexesToReport*:<br><br>4> derive layer 3 filtered RSRP and RSRQ per beam for the serving cell based on SS/PBCH block, as described in 5.5.3.3a;<br><br>3> derive serving cell measurement results based on SS/PBCH block, as described in 5.5.3.3;<br><br>2> if at least one *measId* included in the *measIdList* within *VarMeasConfig* contains an *rsType* set to *csi-rs*:<br><br>3> if at least one *measId* included in the *measIdList* within *VarMeasConfig* contains a *reportQuantityRsIndexes* and *maxNrofRSIndexesToReport*:<br><br>4> derive layer 3 filtered RSRP and RSRQ per beam for the serving cell based on CSI-RS, as described in 5.5.3.3a;<br><br>3> derive serving cell measurement results based on CSI-RS, as described in 5.5.3.3;<br><br>1> if at least one *measId* included in the *measIdList* within *VarMeasConfig* contains SINR as trigger quantity and/or reporting quantity:<br><br>2> if the associated *reportConfig* contains *rsType* set to *ssb*:<br><br>3> if the *measId* contains a *reportQuantityRsIndexes* and *maxNrofRSIndexesToReport*:<br><br>4> derive layer 3 filtered SINR per beam for the serving cell based on SS/PBCH block, as described in 5.5.3.3a;<br><br>3> derive serving cell SINR based on SS/PBCH block, as described in 5.5.3.3; 2> if the associated *reportConfig* contains *rsType* set to *csi-rs*:<br><br>3> if the *measId* contains a *reportQuantityRsIndexes* and *maxNrofRSIndexesToReport*: |

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| | 4> derive layer 3 filtered SINR per beam for the serving cell based on CSI-RS, as described in 5.5.3.3a;<br><br>3> derive serving cell SINR based on CSI-RS, as described in 5.5.3.3;<br><br>1> for each *measId* included in the *measIdList* within *VarMeasConfig*:<br><br>2> if the *reportType* for the associated *reportConfig* is set to *reportCGI*:<br><br>3> perform the corresponding measurements on the frequency and RAT indicated in the associated *measObject* using available idle periods;<br><br>3> if the cell indicated by *reportCGI* field for the associated *measObject* is an NR cell and that indicated cell is broadcasting *SIB1* (see TS 38.213 [13], section 13):<br><br>4> try to acquire *SIB1* in the concerned cell;<br><br>3> if the cell indicated by *reportCGI* field is an EUTRA cell:<br><br>4> try to acquire *SystemInformationBlockType1* in the concerned cell;<br><br>2> if the *reportType* for the associated *reportConfig* is *periodical* or *eventTriggered*:<br><br>3> if a measurement gap configuration is setup, or<br><br>3> if the UE does not require measurement gaps to perform the concerned measurements:<br><br>4> if *s-MeasureConfig* is not configured, or<br><br>4> if *s-MeasureConfig* is set to *ssb-RSRP* and the NR SpCell RSRP based on SS/PBCH block, after layer 3 filtering, is lower than *ssb-RSRP,* or<br><br>4> if *s-MeasureConfig* is set to *csi-RSRP* and the NR SpCell RSRP based on CSI-RS, after layer 3 filtering, is lower than *csi-RSRP*:<br><br>5> if the *measObject* is associated to NR and the *rsType* is set to *csi-rs*: |

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| | 6> if *reportQuantityRsIndexes* and *maxNrofRSIndexesToReport* for the associated *reportConfig* are configured:<br><br>7> derive layer 3 filtered beam measurements only based on CSI-RS for each measurement quantity indicated in *reportQuantityRsIndexes*, as described in 5.5.3.3a;<br><br>6> derive cell measurement results based on CSI-RS for each trigger quantity and each measurement quantity indicated in *reportQuantityCell* using parameters from the associated *measObject*, as described in 5.5.3.3;<br><br>5> if the *measObject* is associated to NR and the *rsType* is set to *ssb*:<br><br>6> if *reportQuantityRsIndexes* and *maxNrofRSIndexesToReport* for the associated *reportConfig* are configured:<br><br>7> derive layer 3 beam measurements only based on SS/PBCH block for each measurement quantity indicated in *reportQuantityRsIndexes*, as described in 5.5.3.3a;<br><br>6> derive cell measurement results based on SS/PBCH block for each trigger quantity and each measurement quantity indicated in *reportQuantityCell* using parameters from the associated *measObject*, as described in 5.5.3.3;<br><br>5> if the *measObject* is associated to E-UTRA:<br><br>6> perform the corresponding measurements associated to neighbouring cells on the frequencies indicated in the concerned *measObject*;<br><br>2> perform the evaluation of reporting criteria as specified in 5.5.4.<br><br>**5.5.3.2 Layer 3 filtering**<br><br>The UE shall:<br><br>1> for each cell measurement quantity and for each beam measurement quantity that the UE performs measurements according to 5.5.3.1: |

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| | … <br><br> 5.5.3.3 Derivation of cell measurement results <br><br> The network may configure the UE to derive RSRP, RSRQ and SINR measurement results per cell associated to NR measurement objects based on parameters configured in the *measObject* (e.g. maximum number of beams to be averaged and beam consolidation thresholds) and in the *reportConfig* (*rsType* to be measured, SS/PBCH block or CSI- RS). <br><br> The UE shall: <br><br> 1> for <br><br> 2> if *nrofSS-BlocksToAverage* in the associated *measObject* is not configured; or <br> 2> if *absThreshSS-BlocksConsolidation* in the associated *measObject* is not configured; or <br> 2> if the highest beam measurement quantity value is below or equal to *absThreshSS-BlocksConsolidation*: <br><br> 3> derive each cell measurement quantity based on SS/PBCH block as the highest beam measurement quantity value, where each beam measurement quantity is described in TS 38.215 [9]; <br><br> 2> else: <br><br> 3> derive each cell measurement quantity based on SS/PBCH block as the linear power scale average of the highest beam measurement quantity values above *absThreshSS-BlocksConsolidation* where the total number of averaged beams shall not exceed *nrofSS-BlocksToAverage*; <br><br> 2> apply layer 3 cell filtering as described in 5.5.3.2; <br><br> 1> for <br><br> each cell measurement quantity to be derived based on CSI-RS: <br><br> each cell measurement quantity to be derived based on SS/PBCH block: |

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| | 2> consider a CSI-RS resource to be applicable for deriving cell measurements when the concerned CSI-RS resource is included in the *csi-rs-CellMobility*includingthe *physCellId* of the cell in the*CSI-RS-ResourceConfigMobility* in the associated *measObject*;<br><br>2> if *nrofCSI-RS-ResourcesToAverage* in the associated *measObject* is not configured; or<br>2> if *absThreshCSI-RS-Consolidation* in the associated *measObject* is not configured; or<br>2> if the highest beam measurement quantity value is below or equal to *absThreshCSI-RS-Consolidation*:<br><br>3> derive each cell measurement quantity based on applicable CSI-RS resources for the cell as the highest beam measurement quantity value, where each beam measurement quantity is described in TS 38.215 [9];<br><br>2> else:<br><br>3> derive each cell measurement quantity based on CSI-RS as the linear power scale average of the highest beam measurement quantity values above *absThreshCSI-RS-Consolidation* where the total number of averaged beams shall not exceed *nrofCSI-RS-ResourcesToAverage*;<br><br>2> apply layer 3 cell filtering as described in 5.5.3.2.<br><br>**5.5.3.3a Derivation of layer 3 beam filtered measurement**<br><br>The UE shall:<br>1> for each layer 3 beam filtered measurement quantity to be derived based on SS/PBCH block;<br><br>2> derive each configured beam measurement quantity based on SS/PBCH block as described in TS 38.215[9], and apply layer 3 beam filtering as described in 5.5.3.2;<br><br>1> for each layer 3 beam filtered measurement quantity to be derived based on CSI-RS;<br><br>2> derive each configured beam measurement quantity based on CSI-RS as described in TS 38.215 [9], and apply layer 3 beam filtering as described in 5.5.3.2.<br><br>… |

## 5.5.5 Measurement reporting

### 5.5.5.1 General


**Figure 5.5.5.1-1: Measurement reporting**

The purpose of this procedure is to transfer measurement results from the UE to the network. The UE shall initiate this procedure only after successful security activation.

For the *measId* for which the measurement reporting procedure was triggered, the UE shall set the *measResults* within the *MeasurementReport* message as follows:

1> set the *measId* to the measurement identity that triggered the measurement reporting;
1> set the *measResultServingCell* within *measResultServingMOList* to include RSRP, RSRQ and the available SINR for each configured serving cell derived based on the *rsType* indicated in the associated *reportConfig*;

1> set the *measResultServingCell* within *measResultServingMOList* to include for each NR serving cell that is configured with *servingCellMO*, if any, the *servCellId*;

1> if the *reportConfig* associated with the *measId* that triggered the measurement reporting includes *reportQuantityRsIndexes* and *maxNrofRSIndexesToReport*:

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| | 2> for each serving cell configured with *servingCellMO*, include beam measurement information according to the associated *reportConfig* as described in 5.5.5.2;<br><br>1> if the *reportConfig* associated with the *measId* that triggered the measurement reporting includes *reportAddNeighMeas*:<br><br>2>for each serving cell *measObjectId* referenced in the *measIdList*, other than the *measObjectId*corresponding with the *measId* that triggered the measurement reporting:<br><br>3> set the *measResultBestNeighCell* within *measResultServingMOList* to include the *physCellId* and the available measurement quantities based on the *reportQuantityCell*and *rsType*indicated in *reportConfig* of the non-serving cell corresponding to the concerned *measObjectNR*with the highest measured RSRP if RSRP measurement results are available for cells corresponding to this *measObjectNR*, otherwise with the highest measured RSRQ if RSRQ measurement results are available for cells corresponding to this *measObjectNR*, otherwise with the highest measured SINR;<br><br>3> if the *reportConfig* associated with the *measId* that triggered the measurement reporting includes *reportQuantityRsIndexes* and *maxNrofRSIndexesToReport:*<br><br>4> for each best non-serving cell included in the measurement report:<br><br>5>include beam measurement information according to the associated *reportConfig* as described in 5.5.5.2;<br><br>1> if there is at least one applicable neighbouring cell to report:<br><br>2> set the *measResultNeighCells* to include the best neighbouring cells up to *maxReportCells* in accordance with the following:<br><br>3> if the *reportType* is set to *eventTriggered*:<br><br>4> include the cells included in the *cellsTriggeredList* as defined within the *VarMeasReportList* for this *measId*;<br><br>3> else: |

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| | 4> include the applicable cells for which the new measurement results became available since the last periodical reporting or since the measurement was initiated or reset;<br><br>4> if *reportQuantityRsIndexes*and *maxNrofRSIndexesToReport* are configured, include beam measurement information as described in 5.5.5.2;<br><br>3> for each cell that is included in the *measResultNeighCells*, include the *physCellId*; 3> if the *reportType* is set to *eventTriggered*:<br><br>4> for each included cell, include the layer 3 filtered measured results in accordance with the *reportConfig* for this *measId*, ordered as follows:<br><br>5> if the *measObject* associated with this *measId* concerns NR:<br><br>6> if *rsType* in the associated *reportConfig* is set to *ssb*:<br><br>7> set *resultsSSB-Cell* within the *measResult* to include the SS/PBCH block based quantity(ies) indicated in the *reportQuantityCell* within the concerned *reportConfig*, in order of decreasing trigger quantity, i.e. the best cell is included first:<br><br>8> if *reportQuantityRsIndexes*and *maxNrofRSIndexesToReport* are configured, include beam measurement information as described in 5.5.5.2;<br><br>6> else if *rsType* in the associated *reportConfig* is set to *csi-rs*:<br><br>7> set *resultsCSI-RS-Cell* within the *measResult* to include the CSI-RS based quantity(ies) indicated in the *reportQuantityCell* within the concerned *reportConfig*, in order of decreasing trigger quantity, i.e. the best cell is included first:<br><br>8> if *reportQuantityRsIndexes*and *maxNrofRSIndexesToReport* are, include beam measurement information as described in 5.5.5.2;<br><br>5> if the *measObject* associated with this *measId* concerns E-UTRA: |

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| | 6> set the *measResult* to include the quantity(ies) indicated in the *reportQuantity* within the concerned *reportConfigInterRAT* in order of decreasing E-UTRA trigger quantity, i.e. the best cell is included first;<br><br>3> if the *reportType* is set to *periodical*:<br><br>4> if a single reporting quantity is set to *TRUE* in *reportQuantityRsIndexes*;<br><br>5> consider the configured single quantity as the sorting quantity;<br><br>4> else:<br><br>5> if *rsrp* is set to TRUE;<br><br>6> consider RSRP as the sorting quantity;<br><br>5> else:<br><br>6> consider RSRQ as the sorting quantity;<br><br>3> if the *reportType* is set to *reportCGI*:<br><br>4> if the cell indicated by *cellForWhichToReportCGI* is an NR cell:<br><br>5> if all mandatory fields of the *cgi-Info* for the concerned cell have been obtained:<br><br>6> include the *plmn-IdentityInfoList* including *plmn-IdentityList*, *trackingAreaCode* (if available), *ranac* (if available) and *cellIdentity* for each entry of the *plmn-IdentityInfoList*;<br><br>6> include *frequencyBandList* if available;<br><br>5> else if MIB indicates the SIB1 is not broadcast:<br><br>6> include the *noSIB1* including the *ssb-SubcarrierOffset* and *pdcch-ConfigSIB1* obtained from MIB of the concerned cell; |

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| | 4> if the cell indicated by *cellForWhichToReportCGI* is an EUTRA cell:<br><br>5> if all mandatory fields of the *cgi-Info-EPC* for the concerned cell have been obtained:<br><br>6> include in the *cgi-Info-EPC* the fields broadcasted in EUTRA *SystemInformationBlockType1* associated to EPC;<br><br>5> if UE is E-UTRA/5GC capable and all mandatory fields of the *cgi-Info-5GC* for the concerned cell have been obtained:<br><br>6> include in the *cgi-Info-5GC* the fields broadcasted in EUTRA *SystemInformationBlockType1* associated to 5GC;<br><br>5> include the *freqBandIndicator*;<br><br>5> if the cell broadcasts the *multiBandInfoList*, include the *multiBandInfoList*;<br><br>5> if the cell broadcasts the *freqBandIndicatorPriority*, include the *freqBandIndicatorPriority*;<br><br>1> increment the *numberOfReportsSent* as defined within the *VarMeasReportList* for this *measId* by 1;<br><br>1> stop the periodical reporting timer, if running;<br><br>1> if the *numberOfReportsSent* as defined within the *VarMeasReportList* for this *measId* is less than the *reportAmount* as defined within the corresponding *reportConfig* for this *measId*:<br><br>2> start the periodical reporting timer with the value of *reportInterval* as defined within the corresponding *reportConfig* for this *measId*;<br><br>1> else:<br><br>2> if the *reportType* is set to *periodical*:<br><br>3> remove the entry within the *VarMeasReportList* for this *measId*; |

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| | 3> remove this *measId* from the *measIdList* within *VarMeasConfig*; 1> if the UE is configured with EN-DC:<br><br>2> if SRB3 is configured:<br><br>3> submit the *MeasurementReport* message via SRB3 to lower layers for transmission, upon which the procedure ends;<br><br>2> else:<br><br>3> submit the *MeasurementReport* message via the EUTRA MCG embedded in E-UTRA RRC message *ULInformationTransferMRDC* as specified in TS 36.331 [10].<br><br>1> else:<br><br>2> submit the *MeasurementReport* message to lower layers for transmission, upon which the procedure ends.<br><br>**5.5.5.2 Reporting of beam measurement information**<br>For beam measurement information to be included in a measurement report the UE shall:<br><br>1> if *reportType* is set to *eventTriggered*:<br><br>2> consider the trigger quantity as the sorting quantity;<br><br>1> if *reportType* is set to *periodical*:<br><br>2> if a single reporting quantity is set to TRUE in *reportQuantityRsIndexes*;<br><br>3> consider the configured single quantity as the sorting quantity;<br><br>2> else:<br><br>3> if *rsrp* is set to TRUE; |

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| | 4> consider RSRP as the sorting quantity;<br><br>3> else:<br><br>4> consider RSRQ as the sorting quantity;<br><br>1> set *rsIndexResults* to include up to *maxNrofRsIndexesToReport*SS/PBCH block indexes or CSI-RS indexes in order of decreasing sorting quantity as follows:<br><br>2> if the measurement information to be included is based on SS/PBCH block:<br><br>3> include within *resultsSSB-Indexes* the index associated to the best beam for that SS/PBCH block sorting quantity and if *absThreshSS-BlocksConsolidation*is included in the *VarMeasConfig* for the corresponding *measObject*, the remaining beams whose sorting quantity is above *absThreshSS-BlocksConsolidation* defined in the *VarMeasConfig* for the corresponding *measObject*;<br><br>3> if *includeBeamMeasurements* is configured, include the SS/PBCH based measurement results for the quantities in *reportQuantityRsIndexes* set to TRUE for each SS/PBCH blockindex;<br><br>2> else if the beam measurement information to be included is based on CSI-RS:<br><br>3> include within *resultsCSI-RS-Indexes* the index associated to the best beam for that CSI-RS sorting quantity and, if *absThreshCSI-RS-Consolidation* is included in the *VarMeasConfig* for the corresponding *measObject*, the remaining beams whose sorting quantity is above *absThreshCSI-RS-Consolidation* defined in the *VarMeasConfig* for the corresponding *measObject*;<br><br>3> if *includeBeamMeasurements*is configured, include the CSI-RS based measurement results for the quantities in *reportQuantityRsIndexes* set to TRUE for each CSI-RS index.<br><br>…<br><br><u>From 3GPP TS 38.133 v15.3.0 Release 15</u>:<br><br>**8.5 Link Recovery Procedures** 8.5.1 Introduction |

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| | The UE shall assess the downlink link quality of a serving cell based on the reference signal in the set $q_0$ as specificed in TS 38.213 [3] in order to detect beam failure instance. The RS resources in the set $q_0$ can be periodic CSI-RS resources and/or SSBs. UE is not required to perform beam failure detection outside the active DL BWP.<br><br>On each RS resource in the set $q_0$, the UE shall estimate the radio link quality and compare it to the threshold $Q_{out\_LR}$ for the purpose of accessing downlink radio link quality of the serving cell.<br><br>The threshold $Q_{out\_LR}$ is defined as the level at which the downlink radio level link cannot be reliably received and shall correspond to the $BLER_{out}$[TBD] block error rate of a hypothetical PDCCH transmission. For SSB based beam failure detection, $Q_{out\_LR\_SSB}$ is derived based on the hypothetical PDCCH transmission parameters listed in Table 8.5.2.1-1. For CSI-RS based beam failure detection, $Q_{out\_LR\_CSI-RS}$ is derived based on the hypothetical PDCCH transmission parameters listed in Table 8.5.3.1-1.<br><br>The UE shall perform L1-RSRP measurements based on the reference signal in the set $q_1$ as specified in TS 38.213 [3] in order to detect candidate beam. The RS resources in the set $q_1$ can be periodic CSI-RS resources and/or SSBs. UE is not required to perform candidate beam detection outside the active DL BWP.<br><br>On each RS resource in the set $q_1$, the UE shall perform L1-RSRP measurements and compare it to the threshold $Q_{in\_LR}$ for the purpose of selecting new beam(s) for beam failure recovery.<br><br>The threshold $Q_{in\_LR}$ corresponds to the value of higher layer parameter *candidateBeamThreshold*.<br><br>…<br><br>*See* 3GPP TS 38.331 v15.3.0, Section 6.3.2, at, *e.g., MeasObject NR* IE.<br><br>*See* 3GPP TS 38.133 version 15.3.0 Release 15 (ETSI TS 138 133 V15.3.0 (2018-10)) at Sections 8.5 (including 8.5.1, 8.5.2, 8.5.3, 8.5.4, 8.5.5, 8.5.6, and 8.5.7).<br><br>*See also* 3GPP TR 38.804 v1.0.0 Release 14 (2017-03), Section 5.3.4 (Beam Reporting), Section 5.5.4 (Measurements).<br><br>3GPP TS 38.331 v15.3.0, Section 6.3.2, at *SRS-Config* IE<br><br>The *SRS-Config* IE is used to configure sounding reference signal transmissions. The configuration defines a list of SRS-Resources and a list of SRS-ResourceSets. Each resource set defines a set of SRS-Resources. The network |

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| | triggers the transmission of the set of SRS-Resources using a configured aperiodicSRS-ResourceTrigger (L1 DCI).<br>…<br><br>*See at* "usage" SRS-ResourceSet field description.<br><br>3GPP TS 38.331 v15.3.0, Section 6.3.2, at *MIMO-Layers* and *MIMO-ParametersPerBand* IE:<br><br>*MIMO-Layers*<br><br>`-- ASN1START`<br><br>`-- TAG-MIMO-LAYERS-START`<br><br>`MIMO-LayersDL ::= ENUMERATED {twoLayers, fourLayers, eightLayers}`<br><br>`MIMO-LayersUL ::= ENUMERATED {oneLayer, twoLayers, fourLayers}`<br><br>`-- TAG-MIMO-LAYERS-STOP`<br>`-- ASN1STOP`<br><br>*MIMO-ParametersPerBand*<br><br>The IE *MIMO-ParametersPerBand* is used to convey MIMO related parameters specific for a certain band (not per feature set or band combination).<br><br>***MIMO-ParametersPerBand* information element**<br><br>`-- ASN1START`<br>`-- TAG-MIMO-PARAMETERSPERBAND-START`<br><br>`MIMO-ParametersPerBand ::= SEQUENCE {`<br>`tci-StatePDSCH SEQUENCE {` |

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        maxNumberConfiguredTCIstatesPerCC   ENUMERATED {n4, n8, n16, n32, n64, n128}                OPTIO
        maxNumberActiveTCI-PerBWP           ENUMERATED {n1, n2, n4, n8}                             OPTIO
    }                                                                                               OPTIO
    additionalActiveTCI-StatePDCCH      ENUMERATED {supported}                                      OPTIO
    pusch-TransCoherence                ENUMERATED {nonCoherent, partialNonCoherent, fullCoherent}  OPTIO
    beamCorrespondence                  ENUMERATED {supported}                                      OPTIO
    periodicBeamReport                  ENUMERATED {supported}                                      OPTIO
    aperiodicBeamReport                 ENUMERATED {supported}                                      OPTIO
    sp-BeamReportPUCCH                  ENUMERATED {supported}                                      OPTIO
    sp-BeamReportPUSCH                  ENUMERATED {supported}                                      OPTIO
    beamManagementSSB-CSI-RS            BeamManagementSSB-CSI-RS                                    OPTIO
    maxNumberRxBeam                     INTEGER (2..8)                                              OPTIO
    maxNumberRxTxBeamSwitchDL           SEQUENCE {
        scs-15kHz                           ENUMERATED {n4, n7, n14}                                OPTIO
        scs-30kHz                           ENUMERATED {n4, n7, n14}                                OPTIO
        scs-60kHz                           ENUMERATED {n4, n7, n14}                                OPTIO
        scs-120kHz                          ENUMERATED {n4, n7, n14}                                OPTIO
        scs-240kHz                          ENUMERATED {n4, n7, n14}                                OPTIO
    }                                                                                               OPTIO
    maxNumberNonGroupBeamReporting      ENUMERATED {n1, n2, n4}                                     OPTIO
    groupBeamReporting                  ENUMERATED {supported}                                      OPTIO
    uplinkBeamManagement                SEQUENCE {
        maxNumberSRS-ResourcePerSet-BM      ENUMERATED {n2, n4, n8, n16},
        maxNumberSRS-ResourceSet            INTEGER (1..8)
    }                                                                                               OPTIO
    maxNumberCSI-RS-BFR                 INTEGER (1..64)                                             OPTIO
    maxNumberSSB-BFR                    INTEGER (1..64)                                             OPTIO
    maxNumberCSI-RS-SSB-BFR             INTEGER (1..256)                                            OPTIO
    twoPortsPTRS-DL                     ENUMERATED {supported}                                      OPTIO
    twoPortsPTRS-UL                     ENUMERATED {supported}                                      OPTIO
    supportedSRS-Resources              SRS-Resources                                               OPTIO
    maxNumberSimultaneousSRS-PerCC      INTEGER (1..4)                                              OPTIO
    beamReportTiming                    SEQUENCE {
        scs-15kHz                           ENUMERATED {sym2, sym4, sym8}                           OPTIO
        scs-30kHz                           ENUMERATED {sym4, sym8, sym14}                          OPTIO
        scs-60kHz                           ENUMERATED {sym8, sym14, sym28}                         OPTIO
        scs-120kHz                          ENUMERATED {sym14, sym28, sym56}                        OPTIO
    }                                                                                               OPTIO
    ptrs-DensityRecommendationSetDL     SEQUENCE {
        scs-15kHz                           PTRS-DensityRecommendationDL                            OPTIO
        scs-30kHz                           PTRS-DensityRecommendationDL                            OPTIO
        scs-60kHz                           PTRS-DensityRecommendationDL                            OPTIO
        scs-120kHz                          PTRS-DensityRecommendationDL                            OPTIO
    }                                                                                               OPTIO
    ptrs-DensityRecommendationSetUL     SEQUENCE {
        scs-15kHz                           PTRS-DensityRecommendationUL                            OPTIO
        scs-30kHz                           PTRS-DensityRecommendationUL                            OPTIO
        scs-60kHz                           PTRS-DensityRecommendationUL                            OPTIO
        scs-120kHz                          PTRS-DensityRecommendationUL                            OPTIO
    }                                                                                               OPTIO
    csi-RS-ForTracking                  CSI-RS-ForTracking                                          OPTIO
    aperiodicTRS                        ENUMERATED {supported}                                      OPTIO
    ...
}
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| | <pre>BeamManagementSSB-CSI-RS ::=        SEQUENCE {<br>    maxNumberSSB-CSI-RS-ResourceOneTx    ENUMERATED {n8, n16, n32, n64},<br>    maxNumberSSB-CSI-RS-ResourceTwoTx    ENUMERATED {n0, n4, n8, n16, n32, n64},<br>    supportedCSI-RS-Density              ENUMERATED {one, three, oneAndThree}<br>}<br><br>CSI-RS-ForTracking ::=              SEQUENCE {<br>    burstLength                          INTEGER (1..2),<br>    maxSimultaneousResourceSetsPerCC     INTEGER (1..8),<br>    maxConfiguredResourceSetsPerCC       INTEGER (1..64),<br>    maxConfiguredResourceSetsAllCC       INTEGER (1..128)<br>}<br><br>PTRS-DensityRecommendationDL ::=    SEQUENCE {<br>    frequencyDensity1                    INTEGER (1..276),<br>    frequencyDensity2                    INTEGER (1..276),<br>    timeDensity1                         INTEGER (0..29),<br>    timeDensity2                         INTEGER (0..29),<br>    timeDensity3                         INTEGER (0..29)<br>}<br><br>PTRS-DensityRecommendationUL ::=    SEQUENCE {<br>    frequencyDensity1                    INTEGER (1..276),<br>    frequencyDensity2                    INTEGER (1..276),<br>    timeDensity1                         INTEGER (0..29),<br>    timeDensity2                         INTEGER (0..29),<br>    timeDensity3                         INTEGER (0..29),<br>    sampleDensity1                       INTEGER (1..276),<br>    sampleDensity2                       INTEGER (1..276),<br>    sampleDensity3                       INTEGER (1..276),<br>    sampleDensity4                       INTEGER (1..276),<br>    sampleDensity5                       INTEGER (1..276)<br>}<br><br>SRS-Resources ::=                   SEQUENCE {<br>    maxNumberAperiodicSRS-PerBWP             ENUMERATED {n1, n2, n4, n8, n16},<br>    maxNumberAperiodicSRS-PerBWP-PerSlot     INTEGER (1..6),<br>    maxNumberPeriodicSRS-PerBWP              ENUMERATED {n1, n2, n4, n8, n16},<br>    maxNumberPeriodicSRS-PerBWP-PerSlot      INTEGER (1..6),<br>    maxNumberSemiPersitentSRS-PerBWP         ENUMERATED {n1, n2, n4, n8, n16},<br>    maxNumberSP-SRS-PerBWP-PerSlot           INTEGER (1..6),<br>    maxNumberSRS-Ports-PerResource           ENUMERATED {n1, n2, n4}<br>}<br><br>SRS-TxSwitch ::=                    SEQUENCE {<br>    supportedSRS-TxPortSwitch            ENUMERATED {t1r2, t1r4, t2r4, t1r4-t2r4, tr-equal},<br>    txSwitchImpactToRx                   ENUMERATED {true}                              OPTIONAL<br>}<br><br>-- ASN1STOP<br>-- TAG-MIMO-PARAMETERSPERBAND-STOP</pre><br><br><u>From 3GPP TS 38.213 v15.3.0 Release 15</u>: |

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| | **6 Link recovery procedures**<br><br>A UE can be provided, for a serving cell, with a set $q_0$ of periodic CSI-RS resource configuration indexes by higher layer parameter *failureDetectionResources* and with a set $q_1$ of periodic CSI-RS resource configuration indexes and/or SS/PBCH block indexes by higher layer parameter *candidateBeamRSList* for radio link quality measurements on the serving cell. If the UE is not provided with higher layer parameter *failureDetectionResources*, the UE determines the set $q_0$ to include periodic CSI-RS resource configuration indexes with same values as the RS indexes in the RS sets indicated by higher layer parameter *TCI-states* for respective control resource sets that the UE uses for monitoring PDCCH. The UE expects the set $q_0$ to include up to two RS indexes and, if there are two RS indexes in a TCI state, the set $q_0$ includes RS indexes with QCL-TypeD configuration for the corresponding TCI states. The UE expects single port RS in the set $q_0$.<br><br>The thresholds $Q_{out,LR}$ and $Q_{in,LR}$ correspond to the default value of higher layer parameter *rlmInSyncOutOfSyncThreshold*, as described in [10, TS38.133] for $Q_{out}$, and to the value provided by higher layer parameter *rsrp-ThresholdSSB*, respectively.<br><br>The physical layer in the UE assesses the radio link quality according to the set $q_0$ of resource configurations against the threshold $Q_{out,LR}$. For the set $q_0$, the UE assesses the radio link quality only according to periodic CSI-RS resource<br><br>configurations or SS/PBCH blocks that are quasi co-located, as described in [6, TS 38.214], with the DM-RS of PDCCH receptions monitored by the UE. The UE applies the $Q_{in,LR}$ threshold to the L1-RSRP measurement obtained from a SS/PBCH block. The UE applies the $Q_{in,LR}$ threshold to the L1-RSRP measurement obtained for a CSI-RS resource after scaling a respective CSI-RS reception power with a value provided by higher layer parameter *powerControlOffsetSS*.<br><br>The physical layer in the UE provides an indication to higher layers when the radio link quality for all corresponding resource configurations in the set $q_0$ that the UE uses to assess the radio link quality is worse than the threshold $Q_{out,LR}$. The physical layer informs the higher layers when the radio link quality is worse than the threshold $Q_{out,LR}$ with a periodicity determined by the maximum between the shortest periodicity among the periodic CSI-RS configurations and/or SS/PBCH blocks in the set $q_0$ that the UE uses to assess the radio link quality and 2 msec. |

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| | Upon request from higher layers, the UE provides to higher layers the periodic CSI-RS configuration indexes and/or SS/PBCH block indexes from the set $q_1$ and the corresponding L1-RSRP measurements that are larger than or equal to the $Q_{in,LR}$ threshold.<br><br>A UE can be provided with a control resource set through a link to a search space set provided by higher layer parameter *recoverySearchSpaceId,* as described in Subclause 10.1, for monitoring PDCCH in the control resource set. If the UE is provided higher layer parameter *recoverySearchSpaceId*, the UE does not expect to be provided another search space set for monitoring PDCCH in the control resource set associated with the search space set provided by *recoverySearchSpaceId*.<br><br>The UE may receive by higher layer parameter *PRACH-ResourceDedicatedBFR*, a configuration for PRACH transmission as described in Subclause 8.1. For PRACH transmission in slot $n$ and according to antenna port quasi co- location parameters associated with periodic CSI-RS resource configuration or with SS/PBCH block associated with index $q_{new}$ provided by higher layers [11, TS 38.321], the UE monitors PDCCH in a search space set provided by higher layer parameter *recoverySearchSpaceId* for detection of a DCI format with CRC scrambled by C-RNTI or MCS- C-RNTI starting from slot $n + 4$ within a window configured by higher layer parameter *BeamFailureRecoveryConfig*. For the PDCCH monitoring and for the corresponding PDSCH reception, the UE assumes the same antenna port quasi- collocation parameters as the ones associated with index $q_{new}$ until the UE receives by higher layers an activation for a TCI state or any of the parameters *TCI-StatesPDCCH-ToAddlist* and/or *TCI-StatesPDCCH-ToReleaseList*. After the UE detects a DCI format with CRC scrambled by C-RNTI or MCS-C-RNTI in the search space set provided by *recoverySearchSpaceId*, the UE continues to monitor PDCCH candidates in the search space set provided by *recoverySearchSpaceId* until the UE receives a MAC CE activation command for a TCI state or higher layer parameters *TCI-StatesPDCCH-ToAddlist* and/or *TCI-StatesPDCCH-ToReleaseList.*<br><br><u>See, e.g., 3GPP TS 38.214 v 16.2.0 R16 (2020-07)</u><br><br>§ 5.2.2.2 Precoding matrix indicator (PMI)<br><br>[describing Type I and Type II and Enhanced Type II Codebooks for MIMO beamforming precoding matrix] |

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| | § 5.2.2.3 Reference signal (CSI-RS)<br><br>§ 5.2.2.4 Channel State Information Interference Measurement CSI-IM<br><br>§ 5.2.3 CSI reporting using PUSCH<br><br>A UE shall perform aperiodic CSI reporting using PUSCH on serving cell c upon successful decoding of a DCI format 0_1 or DCI format 0_2 which triggers an aperiodic CSI trigger state.<br><br>When a DCI format 0_1 schedules two PUSCH allocations, the aperiodic CSI report is carried on the second scheduled PUSCH. When a DCI format 0_1 schedules more than two PUSCH allocations, the aperiodic CSI report is carried on the penultimate scheduled PUSCH.<br><br>An aperiodic CSI report carried on the PUSCH supports wideband, and sub-band frequency granularities. An aperiodic CSI report carried on the PUSCH supports Type I, Type II and Enhanced Type II CSI. A UE shall perform semi-persistent CSI reporting on the PUSCH upon successful decoding of a DCI format 0_1 or DCI format 0_2 which activates a semi-persistent CSI trigger state. DCI format 0_1 and DCI format 0_2 contains a CSI request field which indicates the semi-persistent CSI trigger state to activate or deactivate. Semi-persistent CSI reporting on the PUSCH supports Type I, Type II with wideband, and sub-band frequency granularities and Enhanced Type II CSI. The PUSCH resources and MCS shall be allocated semi-persistently by an uplink DCI. CSI reporting on PUSCH can be multiplexed with uplink data on PUSCH except that semi-persistent CSI reporting on PUSCH activated by a DCI format is not expected to be multiplexed with uplink data on the PUSCH. CSI reporting on PUSCH can also be performed without any multiplexing with uplink data from the UE.<br><br>Type I CSI feedback is supported for CSI Reporting on PUSCH. Type I wideband and sub-band CSI is supported for CSI Reporting on the PUSCH. Type II CSI is supported for CSI Reporting on the PUSCH. |

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| | For Type I, Type II and Enhanced Type II CSI feedback on PUSCH, a CSI report comprises of two parts. Part 1 has a fixed payload size and is used to identify the number of information bits in Part 2. Part 1 shall be transmitted in its entirety before Part 2.<br><br>- For Type I CSI feedback, Part 1 contains RI (if reported), CRI (if reported), CQI for the first codeword (if reported). Part 2 contains PMI (if reported) and contains the CQI for the second codeword (if reported) when RI (if reported) is larger than 4.<br><br>- For Type II CSI feedback, Part 1 contains RI (if reported), CQI, and an indication of the number of non-zero wideband amplitude coefficients per layer for the Type II CSI (see Clause 5.2.2.2.3). The fields of Part 1 – RI (if reported), CQI, and the indication of the number of non-zero wideband amplitude coefficients for each layer – are separately encoded. Part 2 contains the PMI of the Type II CSI. Part 1 and 2 are separately encoded.<br><br>- For Enhanced Type II CSI feedback, Part 1 contains RI, CQI, and an indication of the overall number of nonzero amplitude coefficients across layers for the Enhanced Type II CSI (see Clause 5.2.2.2.5). The fields of Part 1 – RI, CQI, and the indication of the overall number of non-zero amplitude coefficients across layers – are separately encoded. Part 2 contains the PMI of the Enhanced Type II CSI. Part 1 and 2 are separately encoded.<br><br>A Type II CSI report that is carried on the PUSCH shall be computed independently from any Type II CSI report that is carried on the PUCCH formats 3 or 4 (see Clause 5.2.4 and 5.2.2).<br><br>When the higher layer parameter reportQuantity is configured with one of the values 'cri-RSRP', 'ssb-Index-RSRP', 'cri-SINR' or 'ssb-Index-SINR', the CSI feedback consists of a single part.<br><br>For both Type I and Type II reports configured for PUCCH but transmitted on PUSCH, the determination of the payload for CSI part 1 and CSI part 2 follows that of PUCCH as described in Clause 5.2.4.<br><br>When CSI reporting on PUSCH comprises two parts, the UE may omit a portion of the Part 2 CSI. Omission of Part 2 CSI is according to the priority order shown in Table 5.2.3-1, where NRep is the number of CSI reports configured to be carried on the PUSCH. Priority 0 is the |

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| | highest priority and priority 2 N Rep is the lowest priority and the CSI report n corresponds to the CSI report with the nth smallest Prii,CSI(y,k,c,s) value among the NRep CSI reports as defined in Clause 5.2.5. The subbands for a given CSI report n indicated by the higher layer parameter csi-ReportingBand are numbered continuously in increasing order with the lowest subband of csi-ReportingBand as subband 0. When omitting Part 2 CSI information for a particular priority level, the UE shall omit all of the information at that priority level.<br><br>- For Enhanced Type II reports, for a given CSI report $n$, each reported element of indices $i_{2,4,l}$ $i_{2,5,l}$ and $i_{1,7,l}$, indexed by $l$, $i$ and $f$, is associated with a priority value $\mathrm{Pri}(l,i,f) = 2 \cdot L \cdot \upsilon \cdot \pi(f) + \upsilon \cdot i + l$, with $\pi(f) = \min(2 \cdot n_{3,l}^{(f)}, 2 \cdot (N_3 - n_{3,l}^{(f)}) - 1)$ with $l = 1,2,\dots,\upsilon$, $i = 0,1,\dots,2L-1$, and $f = 0,1,\dots,M_\upsilon - 1$, and where $n_{3,l}^{(f)}$ is defined in Clause 5.2.2.2.5. The element with the highest priority has the lowest associated value $\mathrm{Pri}(l,i,f)$. Omission of Part 2 CSI is according to the priority order shown in Table 5.2.3-1, where<br>  - Group 0 includes indices $i_{1,1}$, $i_{1,2}$ and $i_{1,8,l}$ ($l = 1,\dots,\upsilon$).<br><br>- **Group 1 includes indices $i_{1,5}$ (if reported), $i_{1,6,l}$, the $\upsilon 2LM_\upsilon - \lfloor K^{NZ}/2 \rfloor$ highest priority elements of $i_{1,7,l}$, $i_{2,3,l}$, the $\lceil K^{NZ}/2 \rceil - \upsilon$ highest priority elements of $i_{2,4,l}$ and the $\lceil K^{NZ}/2 \rceil - \upsilon$ highest priority elements of $i_{2,5,l}$ ($l = 1,\dots,\upsilon$).**<br>- **Group 2 includes the $\lfloor K^{NZ}/2 \rfloor$ lowest priority elements of $i_{1,7,l}$, the $\lfloor K^{NZ}/2 \rfloor$ lowest priority elements of $i_{2,4,l}$ and the $\lfloor K^{NZ}/2 \rfloor$ lowest priority elements of $i_{2,5,l}$ ($l = 1,\dots,\upsilon$).** |

**Table 5.2.3-1: Priority reporting levels for Part 2 CSI**

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| Priority 0:<br><br>For CSI reports 1 to $N_{Rep}$, Group 0 CSI for CSI reports configured as 'typeII-r16' or 'typeII-PortSelection-r16'; Part 2 wideband CSI for CSI reports configured otherwise |
| Priority 1:<br><br>Group 1 CSI for CSI report 1, if configured as 'typeII-r16' or 'typeII-PortSelection-r16'; Part 2 subband CSI of even subbands for CSI report 1, if configured otherwise |
| Priority 2:<br><br>Group 2 CSI for CSI report 1, if configured as 'typeII-r16' or 'typeII-PortSelection-r16'; Part 2 subband CSI of odd subbands for CSI report 1, if configured otherwise |
| Priority 3:<br><br>Group 1 CSI for CSI report 2, if configured as 'typeII-r16' or 'typeII-PortSelection-r16'; Part 2 subband CSI of even subbands for CSI report 2, if configured otherwise |
| Priority 4:<br><br>Group 2 CSI for CSI report 2, if configured as 'typeII-r16' or 'typeII-PortSelection-r16'. Part 2 subband CSI of odd subbands for CSI report 2, if configured otherwise |

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| Priority $2N_{Rep}-1$:<br><br>Group 1 CSI for CSI report $N_{Rep}$, if configured as 'typeII-r16' or 'typeII-PortSelection-r16'; Part 2 subband CSI of even subbands for CSI report $N_{Rep}$, if configured otherwise |
| Priority $2N_{Rep}$:<br><br>Group 2 CSI for CSI report $N_{Rep}$, if configured as 'typeII-r16' or 'typeII-PortSelection-r16'; Part 2 subband CSI of odd subbands for CSI report $N_{Rep}$, if configured otherwise |

When the UE is scheduled to transmit a transport block on PUSCH multiplexed with a CSI report(s), Part 2 CSI is omitted only when $\left\lceil (O_{\text{CSI-2}} + L_{\text{CSI-2}}) \cdot \beta_{\text{offset}}^{\text{PUSCH}} \cdot \sum_{l=0}^{N_{\text{symb,all}}^{\text{PUSCH}}-1} M_{\text{sc}}^{\text{UCI}}(l) \Big/ \sum_{r=0}^{C_{\text{UL-SCH}}-1} K_r \right\rceil$ is larger than

$\left\lceil \alpha \cdot \sum_{l=0}^{N_{symb,all}^{PUSCH}-1} M_{SC}^{UCI}(l) \right\rceil - Q'_{ACK} - Q'_{CSI-1}$, where parameters $O_{CSI-2}$, $L_{CSI-2}$, $\beta_{offset}^{PUSCH}$, $N_{symb,all}^{PUSCH}$, $M_{sc}^{UCI}(l)$, $C_{UL\text{-}SCH}$, $K_r$, $Q'_{CSI\text{-}1}$, $Q'_{ACK}$ and $\alpha$ are defined in Clause 6.3.2.4 of [5, TS 38.212].

Part 2 CSI is omitted level by level, beginning with the lowest priority level until the lowest priority level is reached which causes the $\left\lceil (O_{CSI\text{-}2} + L_{CSI\text{-}2}) \cdot \beta_{offset}^{PUSCH} \cdot \sum_{l=0}^{N_{symb,all}^{PUSCH}-1} M_{sc}^{UCI}(l) \Big/ \sum_{r=0}^{C_{UL\text{-}SCH}-1} K_r \right\rceil$ to be less than or equal to

$\left\lceil \alpha \cdot \sum_{l=0}^{N_{symb,all}^{PUSCH}-1} M_{SC}^{UCI}(l) \right\rceil - Q'_{ACK} - Q'_{CSI-1}$.

When part 2 CSI is transmitted on PUSCH with no transport block, lower priority bits are omitted until Part 2 CSI code rate, which is given by $(O_{CSI\text{-}2} + L_{CSI\text{-}2})/(N_L \cdot Q'_{CSI,2} \cdot Q_m)$ where $O_{CSI\text{-}2}, L_{CSI\text{-}2}, N_L, Q'_{CSI,2}, Q_m$ are given in clause 6.3.2.4 of [5, 38.212] before HARQ-ACK puncturing part 2 CSI if any, is below a threshold code rate $c_T$ lower than one, where

$$c_T = \frac{R}{\beta_{offset}^{CSI\text{-}part2}}$$

- $\beta_{offset}^{CSI\text{-}part2}$ is the CSI offset value from Table 9.3-2 of [6, TS 38.213]
- $R$ is signaled code rate in DCI

If the UE is in an active semi-persistent CSI reporting configuration on PUSCH, the CSI reporting is deactivated when either the downlink BWP or the uplink BWP is changed. Another activation command is required to enable the semi-persistent CSI reporting.

## § 5.2.4 CSI reporting using PUCCH

A UE is semi-statically configured by higher layers to perform periodic CSI Reporting on the PUCCH. A UE can be configured by higher layers for multiple periodic CSI Reports corresponding to multiple higher layer configured CSI Reporting Settings, where the associated CSI Resource Settings are higher layer configured. Periodic CSI reporting on PUCCH formats 2, 3, 4 supports Type I CSI with wideband granularity.

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| | A UE shall perform semi-persistent CSI reporting on the PUCCH applied starting from the first slot that is after slot $n + 3 N^{subframe,\mu}{}_{slot}$ when the UE would transmit a PUCCH with HARQ-ACK information in slot n corresponding to the PDSCH carrying the activation command described in clause 6.1.3.16 of [10, TS 38.321] where μ is the SCS configuration for the PUCCH. The activation command will contain one or more Reporting Settings where the associated CSI Resource Settings are configured. Semi-persistent CSI reporting on the PUCCH supports Type I CSI. Semi-persistent CSI reporting on the PUCCH format 2 supports Type I CSI with wideband frequency granularity. Semipersistent CSI reporting on PUCCH formats 3 or 4 supports Type I CSI with wideband and sub-band frequency granularities and Type II CSI Part 1.<br><br>When the PUCCH carry Type I CSI with wideband frequency granularity, the CSI payload carried by the PUCCH format 2 and PUCCH formats 3, or 4 are identical and the same irrespective of RI (if reported), CRI (if reported). For type I CSI sub-band reporting on PUCCH formats 3, or 4, the payload is split into two parts. The first part contains RI (if reported), CRI (if reported), CQI for the first codeword. The second part contains PMI and contains the CQI for the second codeword when RI > 4.<br><br>A semi-persistent report carried on the PUCCH formats 3 or 4 supports Type II CSI feedback, but only Part 1 of Type II CSI feedback (See Clause 5.2.2 and 5.2.3). Supporting Type II CSI reporting on the PUCCH formats 3 or 4 is a UE capability type2-SP-CSI-Feedback-LongPUCCH. A Type II CSI report (Part 1 only) carried on PUCCH formats 3 or 4 shall be calculated independently of any Type II CSI reports carried on the PUSCH (see Clause 5.2.3).<br><br>When the UE is configured with CSI Reporting on PUCCH formats 2, 3 or 4, each PUCCH resource is configured for each candidate UL BWP.<br><br>If the UE is in an active semi-persistent CSI reporting configuration on PUCCH and has not received a deactivation command, the CSI reporting takes place when the BWP in which the reporting is configured to take place is the active BWP, otherwise the CSI reporting is suspended. |

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| | A UE is not expected to report CSI with a total number of UCI bits and CRC bits larger than 115 bits when configured with PUCCH format 4. For CSI reports transmitted on a PUCCH, if all CSI reports consist of one part, the UE may omit a portion of CSI reports. Omission of CSI is according to the priority order determined from the Prii,CSI(y,k,c,s) value as defined in Clause 5.2.5. CSI report is omitted beginning with the lowest priority level until the CSI report code rate is less or equal to the one configured by the higher layer parameter maxCodeRate.<br><br>If any of the CSI reports consist of two parts, the UE may omit a portion of Part 2 CSI. Omission of Part 2 CSI is according to the priority order shown in Table 5.2.3-1. Part 2 CSI is omitted beginning with the lowest priority level until the Part 2 CSI code rate is less or equal to the one configured by higher layer parameter maxCodeRate.<br><br>…<br><br>**§ 6.1.1.1 Codebook based UL transmission**<br><br>For codebook based transmission, PUSCH can be scheduled by DCI format 0_0, DCI format 0_1, DCI format 0_2 or semi-statically configured to operate according to Clause 6.1.2.3. If this PUSCH is scheduled by DCI format 0_1, DCI format 0_2, or semi-statically configured to operate according to Clause 6.1.2.3, the UE determines its PUSCH transmission precoder based on SRI, TPMI and the transmission rank, where the SRI, TPMI and the transmission rank are given by DCI fields of SRS resource indicator and Precoding information and number of layers in clause 7.3.1.1.2 and 7.3.1.1.3 of [5, TS 38.212] for DCI format 0_1 and 0_2 or given by srs-ResourceIndicator and precodingAndNumberOfLayers according to clause 6.1.2.3. The SRS-ResourceSet(s) applicable for PUSCH scheduled by DCI format 0_1 and DCI format 0_2 are defined by the entries of the higher layer parameter srs-ResourceSetToAddModList and srs-ResourceSetToAddModList-ForDCIFormat0_2 in SRS-config, respectively. The<br><br>TPMI is used to indicate the precoder to be applied over the layers {0…ν-1} and that corresponds to the SRS resource selected by the SRI when multiple SRS resources are configured, or if a single SRS resource is configured TPMI is used to indicate the precoder to be applied over the layers {0…ν-1} and that corresponds to the SRS resource. The transmission precoder is selected from the uplink codebook that has a number of antenna ports equal to |

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| | higher layer parameter nrofSRS-Ports in SRS-Config, as defined in Clause 6.3.1.5 of [4, TS 38.211]. When the UE is configured with the higher layer parameter txConfig set to 'codebook', the UE is configured with at least one SRS resource. The indicated SRI in slot n is associated with the most recent transmission of SRS resource identified by the SRI, where the SRS resource is prior to the PDCCH carrying the SRI.<br><br>For codebook based transmission, the UE determines its codebook subsets based on TPMI and upon the reception of higher layer parameter codebookSubset in pusch-Config for PUSCH associated with DCI format 0_1 and codebookSubset-ForDCIFormat0_2 in pusch-Config for PUSCH associated with DCI format 0_2 which may be configured with 'fullyAndPartialAndNonCoherent', or 'partialAndNonCoherent', or 'nonCoherent' depending on the UE capability. When higher layer parameter ul-FullPowerTransmission is set to 'fullpowerMode2' and the higher layer parameter codebookSubset or the higher layer parameter codebookSubset-ForDCIFormat0_2 is set to 'partialAndNonCoherent', and when the SRS-resourceSet with usage set to "codebook" includes at least one SRS resource with 4 ports and one SRS resource with 2 ports, the codebookSubset associated with the 2-port SRS resource is 'nonCoherent'. The maximum transmission rank may be configured by the higher layer parameter maxRank in pusch-Config for PUSCH scheduled with DCI format 0_1 and maxRank-ForDCIFormat0_2 for PUSCH scheduled with DCI format 0_2.<br><br>A UE reporting its UE capability of 'partialAndNonCoherent' transmission shall not expect to be configured by either codebookSubset or codebookSubset-ForDCIFormat0_2 with 'fullyAndPartialAndNonCoherent'.<br><br>A UE reporting its UE capability of 'nonCoherent' transmission shall not expect to be configured by either codebookSubset or codebookSubset-ForDCIFormat0_2 with 'fullyAndPartialAndNonCoherent' or with 'partialAndNonCoherent'.<br><br>A UE shall not expect to be configured with the higher layer parameter codebookSubset or the higher layer parameter codebookSubset-ForDCIFormat0_2 set to 'partialAndNonCoherent' when higher layer parameter nrofSRS-Ports in an SRS-ResourceSet with usage set to 'codebook' |

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| | indicates that the maximum number of the configured SRS antenna ports in the SRS-ResourceSet is two.<br><br>For codebook based transmission, the UE may be configured with a single SRS-ResourceSet with usage set to 'codebook' and only one SRS resource can be indicated based on the SRI from within the SRS resource set. Except when higher layer parameter ul-FullPowerTransmission is set to 'fullpowerMode2', the maximum number of configured SRS resources for codebook based transmission is 2. If aperiodic SRS is configured for a UE, the SRS request field in DCI triggers the transmission of aperiodic SRS resources.<br><br>A UE shall not expect to be configured with higher layer parameter ul-FullPowerTransmission set to 'fullpowerMode1' and codebookSubset or codebookSubset-ForDCIFormat0_2 set to 'fullAndPartialAndNonCoherent' simultaneously.<br><br>The UE shall transmit PUSCH using the same antenna port(s) as the SRS port(s) in the SRS resource indicated by the DCI format 0_1 or 0_2 or by configuredGrantConfig according to clause 6.1.2.3.<br><br>The DM-RS antenna ports in Clause 6.4.1.1.3 of [4, TS38.211] are determined according to the ordering of DM-RS port(s) given by Tables 7.3.1.1.2-6 to 7.3.1.1.2-23 in Clause 7.3.1.1.2 of [5, TS 38.212].<br><br>Except when higher layer parameter ul-FullPowerTransmission is set to 'fullpowerMode2', when multiple SRS resources are configured by SRS-ResourceSet with usage set to 'codebook', the UE shall expect that higher layer parameters nrofSRS-Ports in SRS-Resource in SRS-ResourceSet shall be configured with the same value for all these SRS resources.<br><br>When higher layer parameter ul-FullPowerTransmission is set to 'fullpowerMode2',<br><br>- the UE can be configured with one SRS resource or multiple SRS resources with same or different number of SRS ports within an SRS resource set with usage set to 'codebook'. |

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| | - up to 2 different spatial relations can be configured for all SRS resources in the SRS resource set with usage set to 'codebook' when multiple SRS resources are configured in the SRS resource set.<br><br>- subject to UE capability, a maximum of 2 or 4 SRS resources are supported in an SRS resource set with usage set to 'codebook'<br><br>**§ 6.1.1.2 Non-Codebook based UL transmission**<br><br>For non-codebook based transmission, PUSCH can be scheduled by DCI format 0_0, DCI format 0_1, DCI format 0_2 or semi-statically configured to operate according to Clause 6.1.2.3. If this PUSCH is scheduled by DCI format 0_1, DCI format 0_2, or semi-statically configured to operate according to Clause 6.1.2.3, the UE can determine its PUSCH precoder and transmission rank based on the SRI when multiple SRS resources are configured, where the SRI is given by the SRS resource indicator in DCI according to clause 7.3.1.1.2 and 7.3.1.1.3 of [5, 38.212] for DCI format 0_1 and DCI format 0_2, or the SRI is given by srs-ResourceIndicator according to clause 6.1.2.3. The SRS-ResourceSet(s) applicable for PUSCH scheduled by DCI format 0_1 and DCI format 0_2 are defined by the entries of the higher layer parameter srs-ResourceSetToAddModList and srs-ResourceSetToAddModList-ForDCIFormat0_2 in SRS-config, respectively. The UE shall use one or multiple SRS resources for SRS transmission, where, in a SRS resource set, the maximum number of SRS resources which can be configured to the UE for simultaneous transmission in the same symbol and the maximum number of SRS resources are UE capabilities. The SRS resources transmitted simultaneously occupy the same RBs. Only one SRS port for each SRS resource is configured. Only one SRS resource set can be configured with higher layer parameter usage in SRS-ResourceSet set to 'nonCodebook'. The maximum number of SRS resources that can be configured for non-codebook based uplink transmission is 4. The indicated SRI in slot n is associated with the most recent transmission of SRS resource(s) identified by the SRI, where the SRS transmission is prior to the PDCCH carrying the SRI. For non-codebook based transmission, the UE can calculate the precoder used for the transmission of SRS based on measurement of an associated NZP CSI-RS resource. A UE can be configured with only one NZP CSI-RS resource for the SRS resource set with higher layer parameter usage in SRS-ResourceSet set to 'nonCodebook' if configured. |

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| | … <br><br> § 6.2.1 UE sounding procedure <br><br> The UE may be configured with one or more Sounding Reference Signal (SRS) resource sets as configured by the higher layer parameter SRS-ResourceSet or SRS-PosResourceSet-r16. For each SRS resource set configured by SRSResourceSet, a UE may be configured with K ≥1SRS resources (higher layer parameter SRS-Resource), where the maximum value of K is indicated by UE capability [13, 38.306]. When SRS is configured with the higher layer parameter SRS-PosResourceSet-r16, a UE may be configured with SRS resources (higher layer parameter SRSPosResource-r16), where the maximum value of K is 16. The SRS resource set applicability is configured by the higher layer parameter usage in SRS-ResourceSet. When the higher layer parameter usage is set to 'beamManagement', only one SRS resource in each of multiple SRS sets may be transmitted at a given time instant, but the SRS resources in different SRS resource sets with the same time domain behaviour in the same BWP may be transmitted simultaneously. For aperiodic SRS at least one state of the DCI field is used to select at least one out of the configured SRS resource set(s). The following SRS parameters are semi-statically configurable by higher layer parameter SRS-Resource or SRSPosResource-r16. <br><br> [Describing SRS configurations]: <br><br> The following SRS parameters are semi-statically configurable by higher layer parameter SRS-Resource or SRSPosResource-r16. <br><br> - srs-ResourceId or SRS-PosResourceId-r16 determines SRS resource configuration identity. <br><br> - Number of SRS ports as defined by the higher layer parameter nrofSRS-Ports and described in Clause 6.4.1.4 of [4, TS 38.211]. If not configured, nrofSRS-Ports is 1. <br><br> - Time domain behaviour of SRS resource configuration as indicated by the higher layer parameter resourceType, which may be periodic, semi-persistent, aperiodic SRS transmission as defined in Clause 6.4.1.4 of [4, TS 38.211]. |

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| | - Slot level periodicity and slot level offset as defined by the higher layer parameters periodicityAndOffset-p or periodicityAndOffset-sp for an SRS resource of type periodic or semi-persistent. The UE is not expected to be configured with SRS resources in the same SRS resource set SRS-ResourceSet or SRS-PosResourceSet-r16 with different slot level periodicities. For an SRS-ResourceSet configured with higher layer parameter resourceType set to 'aperiodic', a slot level offset is defined by the higher layer parameter slotOffset. For an RSPosResourceSet-r16 with higher layer parameter resourceType set to 'aperiodic', the slot level offset is defined by the higher layer parameter slotOffset for each SRS resource.<br><br>- Number of OFDM symbols in the SRS resource, starting OFDM symbol of the SRS resource within a slot including repetition factor R as defined by the higher layer parameter resourceMapping and described in Clause<br><br>6.4.1.4 of [4, TS 38.211]. If R is not configured, then R is equal to the number of OFDM symbols in the SRS resource.<br><br>- SRS bandwidth BSRS and CSRS , as defined by the higher layer parameter freqHopping and described in Clause 6.4.1.4 of [4, TS 38.211]. If not configured, then BSRS = 0. - Frequency hopping bandwidth, b hop , as defined by the higher layer parameter freqHopping and described in Clause 6.4.1.4 of [4, TS 38.211]. If not configured, then b hop = 0.<br><br>- Defining frequency domain position and configurable shift, as defined by the higher layer parameters freqDomainPosition and freqDomainShift, respectively, and described in Clause 6.4.1.4 of [4, TS 38.211]. If freqDomainPosition is not configured, freqDomainPosition is zero.<br><br>- Cyclic shift, as defined by the higher layer parameter cyclicShift-n2, cyclicShift-n4, or cyclicShift-n8 for transmission comb value 2, 4 and 8, respectively, and described in Clause 6.4.1.4 of [4, TS 38.211].<br><br>- Transmission comb value as defined by the higher layer parameter transmissionComb described in Clause 6.4.1.4 of [4, TS 38.211]. |

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| | - Transmission comb offset as defined by the higher layer parameter combOffset-n2, combOffset-n4, or combOffset-n8 for transmission comb value 2, 4, or 8 respectively, and described in Clause 6.4.1.4 of [4, TS 38.211].<br><br>- SRS sequence ID as defined by the higher layer parameter sequenceId in Clause 6.4.1.4 of [4].<br><br>- The configuration of the spatial relation between a reference RS and the target SRS, where the higher layer parameter spatialRelationInfo or spatialRelationInfoPos-r16, if configured, contains the ID of the reference RS.The reference RS may be an SS/PBCH block, CSI-RS configured on serving cell indicated by higher layer parameter servingCellId if present, same serving cell as the target SRS otherwise, or an SRS configured on uplink BWP indicated by the higher layer parameter uplinkBWP, and serving cell indicated by the higher layer parameter servingCellId if present, same serving cell as the target SRS otherwise. When SRS is configured by the higher layer parameter SRS-PosResourceSet-r16 the reference RS may also be a DL PRS configured on a serving cell, an SS/PBCH block or a DL PRS of a non-serving cell indicated by a higher layer parameter.<br><br>The UE may be configured by the higher layer parameter resourceMapping in SRS-Resource with an SRS resource occupying {1, 2, 4} S N ∈ adjacent OFDM symbols at any symbol location within the slot, where all antenna ports of the SRS resources are mapped to each symbol of the resource. When the SRS is configured with the higher layer parameter SRS-PosResourceSet-r16 the higher layer parameter resourceMapping in SRS-PosResource-r16 with an SRS resource occupying ∈ 1,2,4,8,12 adjacent symbols anywhere within the slot.<br><br>If a PUSCH with a priority index 0 and SRS configured by SRS-Resource are transmitted in the same slot on a serving cell, the UE may only be configured to transmit SRS after the transmission of the PUSCH and the corresponding DMRS.<br><br>If a PUSCH transmission with a priority index 1 or a PUCCH transmission with a priority index 1 would overlap in time with an SRS transmission on a serving cell, the UE does not transmit the SRS in the overlapping symbol(s). |

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| | For a UE configured with one or more SRS resource configuration(s), and when the higher layer parameter resourceType in SRS-Resource or SRS-PosResource-r16 is set to 'periodic':<br><br>- if the UE is configured with the higher layer parameter spatialRelationInfo or spatialRelationInfoPos-r16 containing the ID of a reference 'ssb-Index', 'ssb-IndexServing-r16', or 'ssb-IndexNcell-r16', the UE shall transmit the target SRS resource with the same spatial domain transmission filter used for the reception of the reference SS/PBCH block, if the higher layer parameter spatialRelationInfo or spatialRelationInfoPos-r16 contains the ID of a reference 'csi-RS-Index' or 'csi-RS-IndexServing-r16', the UE shall transmit the target SRS resource with the same spatial domain transmission filter used for the reception of the reference periodic CSI-RS or of the reference semi-persistent CSI-RS, if the higher layer parameter spatialRelationInfo or spatialRelationInfoPos-r16 containing the ID of a reference 'srs' or 'srs-spatialRelation-r16', the UE shall transmit the target SRS resource with the same spatial domain transmission filter used for the transmission of the reference periodic SRS. When the SRS is configured by the higher layer parameter SRS-PosResource-r16 and if the higher layer parameter spatialRelationInfoPos-r16 contains the ID of a reference 'dl-PRS-ResourceId-r16', the UE shall transmit the target SRS resource with the same spatial domain transmission filter used for the reception of the reference DL PRS.<br><br>For a UE configured with one or more SRS resource configuration(s), and when the higher layer parameter resourceType in SRS-Resource or SRS-PosResource-r16 is set to 'semi-persistent':<br><br>- when a UE receives an activation command, as described in clause 6.1.3.17 or 6.1.3.36 of [10, TS 38.321], for an SRS resource, and when the UE would transmit a PUCCH with HARQ-ACK information in slot n corresponding to the PDSCH carrying the activation command is transmitted in slot n, the corresponding actions in [10, TS 38.321] and the UE assumptions on SRS transmission corresponding to the configured SRS resource set shall be applied starting from the first slot that is after slot $n + 3\ N^{\text{subframe, u}}_{\text{slot}}$ ,µ where µ is the SCS configuration for the PUCCH. The activation command also contains spatial relation assumptions provided by a list of references to reference signal IDs, one per element of the activated SRS resource set. |

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| | When the SRS is configured with the higher layer parameter SRS-ResourceSet, each ID in the list refers to a reference SS/PBCH block, NZP CSI-RS resource configured on serving cell indicated by Resource Serving Cell ID field in the activation command if present, same serving cell as the SRS resource set otherwise, or SRS resource configured on serving cell and uplink bandwidth part indicated by Resource Serving Cell ID field and Resource BWP ID field in the activation command if present, same serving cell and bandwidth part as the SRS resource set otherwise. When the SRS is configured with the higher layer parameter SRS-PosResourceSet-r16, each ID in the list of reference signal IDs may refer to a reference SS/PBCH block on a serving or non-serving cell indicated by PCI field in the activation command, NZP CSI-RS resource configured on serving cell indicated by Resource Serving Cell ID field in the activation command if present, same serving cell as the SRS resource set otherwise, or SRS resource configured on serving cell and uplink bandwidth part indicated by Resource Serving Cell ID field and Resource BWP ID field in the activation command if present, same serving cell and bandwidth part as the SRS resource set otherwise, or DL PRS of a serving or non-serving cell indicated by a higher layer parameter.<br><br>- if an SRS resource in the activated resource set is configured with the higher layer parameter spatialRelationInfo or spatialRelationInfoPos-r16, the UE shall assume that the ID of the reference signal in the activation command overrides the one configured in spatialRelationInfo or spatialRelationInfoPos-r16.<br><br>- when a UE receives a deactivation command [10, TS 38.321] for an activated SRS resource set, and when the UE would transmit a PUCCH with HARQ-ACK information in slot n corresponding to the PDSCH carrying the deactivation command, the corresponding actions in [10, TS 38.321] and UE assumption on cessation of SRS transmission corresponding to the deactivated SRS resource set shall apply starting from the first slot that is after slot n + 3 N $^{\text{subframe, u}}$ $_{\text{slot}}$ ,μ where μ is the SCS configuration for the PUCCH.<br><br>- if the UE is configured with the higher layer parameter spatialRelationInfo or spatialRelationInfoPos-r16 containing the ID of a reference 'ssb-Index', 'ssb-IndexServing-r16', or 'ssb-IndexNcell-r16' the UE shall transmit the target SRS resource with the same spatial domain transmission filter used for the reception of the reference SS/PBCH block, if the higher layer parameter spatialRelationInfo or spatialRelationInfoPos-r16 contains the ID of a reference |

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| | 'csi-RS-Index' or 'csi-RS-IndexServing-r16', the UE shall transmit the target SRS resource with the same spatial domain transmission filter used for the reception of the reference periodic CSI-RS or of the reference semi-persistent CSI-RS, if the higher layer parameter spatialRelationInfo or spatialRelationInfoPosr16 contains the ID of a reference 'srs' or 'srs-SpatialRelation-r16', the UE shall transmit the target SRS resource with the same spatial domain transmission filter used for the transmission of the reference periodic SRS or of the reference semi-persistent SRS. When the SRS is configured by the higher layer parameter SRS-PosResourceSet and if the higher layer parameter spatialRelationInfoPos-r16 contains the ID of a reference 'dl-PRS-ResourceIdr16', the UE shall transmit the target SRS resource with the same spatial domain transmission filter used for the reception of the reference DL PRS.<br><br>If the UE has an active semi-persistent SRS resource configuration and has not received a deactivation command, the semi-persistent SRS configuration is considered to be active in the UL BWP which is active, otherwise it is considered suspended.<br><br>For a UE configured with one or more SRS resource configuration(s), and when the higher layer parameter resourceType in SRS-Resource or SRS-PosResource-r16 is set to 'aperiodic':<br><br>- the UE receives a configuration of SRS resource sets,<br><br>- the UE receives a downlink DCI, a group common DCI, or an uplink DCI based command where a codepoint of the DCI may trigger one or more SRS resource set(s). For SRS in a resource set with usage set to 'codebook' or 'antennaSwitching', the minimal time interval between the last symbol of the PDCCH triggering the aperiodic SRS transmission and the first symbol of SRS resource is N2 + Tswitch. Otherwise, the minimal time interval between the last symbol of the PDCCH triggering the aperiodic SRS transmission and the first symbol of SRS resource is N2 + Tswitch+14. The minimal time interval in units of OFDM symbols is counted based on the minimum subcarrier spacing between the PDCCH and the aperiodic SRS.<br><br>- Tswitch is defined in clause 6.4. |

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| | - If the UE receives the DCI triggering aperiodic SRS in slot n and except when SRS is configured with the higher layer parameter SRS-PosResource-r16, the UE transmits aperiodic SRS in each of the triggered SRS resource |

- If the UE receives the DCI triggering aperiodic SRS in slot $n$ and except when SRS is configured with the higher layer parameter *SRS-PosResource-r16*, the UE transmits aperiodic SRS in each of the triggered SRS resource set(s) in slot $\left\lfloor n\cdot\frac{2^{\mu_{SRS}}}{2^{\mu_{PDCCH}}}\right\rfloor + k + \left\lfloor\left(\frac{N_{slot,offset,PDCCH}^{CA}}{2^{\mu_{offset,PDCCH}}} - \frac{N_{slot,offset,SRS}^{CA}}{2^{\mu_{offset,SRS}}}\right)\cdot 2^{\mu_{SRS}}\right\rfloor$, if UE is configured with *ca-SlotOffset* for at least one of the triggered and triggering cell, $K_s = \left\lfloor n\cdot\frac{2^{\mu_{SRS}}}{2^{\mu_{PDCCH}}}\right\rfloor + k$, otherwise, and where
  - $k$ is configured via higher layer parameter *slotOffset* for each triggered SRS resources set and is based on the subcarrier spacing of the triggered SRS transmission, $\mu_{SRS}$ and $\mu_{PDCCH}$ are the subcarrier spacing configurations for triggered SRS and PDCCH carrying the triggering command respectively;
  - $N_{\text{slot, offset, PDCCH}}^{\text{CA}}$ and $\mu_{\text{offset, PDCCH}}$ are the $N_{\text{slot, offset}}^{\text{CA}}$ and the $\mu_{\text{offset}}$, respectively, which are determined by higher-layer configured *ca-SlotOffset* for the cell receiving the PDCCH, $N_{slot,offset,SRS}^{CA}$ and $\mu_{offset,SRS}$ are the $N_{slot,offset}^{CA}$ and the $\mu_{\text{offset}}$, respectively, which are determined by higher-layer configured *ca-SlotOffset* for the cell transmitting the SRS, as defined in [4, TS 38.211] clause 4.5.
- If the UE receives the DCI triggering aperiodic SRS in slot $n$ and when SRS is configured with the higher layer parameter *SRS-PosResource-r16*, the UE transmits every aperiodic SRS resource in each of the triggered SRS resource set(s) in slot $\left\lfloor n\cdot\frac{2^{\mu_{SRS}}}{2^{\mu_{PDCCH}}}\right\rfloor + k + \left\lfloor\left(\frac{N_{slot,offset,PDCCH}^{CA}}{2^{\mu_{offset,PDCCH}}} - \frac{N_{slot,offset,SRS}^{CA}}{2^{\mu_{offset,SRS}}}\right)\cdot 2^{\mu_{SRS}}\right\rfloor$, if UE is configured with *ca-SlotOffset* for at least one of the triggered and triggering cell, $K_s = \left\lfloor n\cdot\frac{2^{\mu_{SRS}}}{2^{\mu_{PDCCH}}}\right\rfloor + k$, otherwise, and where
  - $k$ is configured via higher layer parameter *slotOffset* for each aperiodic SRS resource in each triggered SRS resources set and is based on the subcarrier spacing of the triggered SRS transmission, $\mu_{SRS}$ and $\mu_{PDCCH}$ are the subcarrier spacing configurations for triggered SRS and PDCCH carrying the triggering command respectively;
  - $N_{\text{slot, offset, PDCCH}}^{\text{CA}}$ and $\mu_{\text{offset, PDCCH}}$ are the $N_{\text{slot, offset}}^{\text{CA}}$ and the $\mu_{\text{offset}}$, respectively, which are determined by higher-layer configured *ca-SlotOffset* for the cell receiving the PDCCH, $N_{slot,offset,SRS}^{CA}$ and $\mu_{offset,SRS}$ are the $N_{slot,offset}^{CA}$ and the $\mu_{\text{offset}}$, respectively, which are determined by higher-layer configured *ca-SlotOffset* for the cell transmitting the SRS, as defined in [4, TS 38.211] clause 4.5.

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| | if the UE is configured with the higher layer parameter spatialRelationInfo or spatialRelationInfoPos-r16 containing the ID of a reference 'ssb-Index', 'ssb-IndexServing-r16' or 'ssb-IndexNcell-r16', the UE shall transmit the target SRS resource with the same spatial domain transmission filter used for the reception of the reference SS/PBCH block, if the higher layer parameter spatialRelationInfo or spatialRelationInfoPos-r16 contains the ID of a reference 'csi-RS-Index' or 'csi-RS-IndexServing-r16', the UE shall transmit the target SRS resource with the same spatial domain transmission filter used for the reception of the reference periodic CSI-RS or of the reference semi-persistent CSI-RS, or of the latest reference aperiodic CSI-RS. If the higher layer parameter spatialRelationInfo or spatialRelationInfoPos-r16 contains the ID of a reference 'srs' or 'srs-SpatialRelation-r16', the UE shall transmit the target SRS resource with the same spatial domain transmission filter used for the transmission of the reference periodic SRS or of the reference semi-persistent SRS or of the reference aperiodic SRS. When the SRS is configured by the higher layer parameter SRS-PosResourceSet-r16 and if the higher layer parameter spatialRelationInfoPos-r16 contains the ID of a reference 'dl-PRS-ResourceId-r16', the UE shall transmit the target SRS resource with the same spatial domain transmission filter used for the reception of the reference DL PRS.<br><br>- when a UE receives an spatial relation update command, as described in clause 6.1.3.26 of [10, TS 38.321], for an SRS resource, and when the HARQ-ACK corresponding to the PDSCH carrying the update command is transmitted in slot n, the corresponding actions in [10, TS 38.321] and the UE assumptions on updating spatial relation for the SRS resource shall be applied for SRS transmission starting from the first slot that is after slot + 3 N ,µ. The update command contains spatial relation assumptions provided by a list of references to reference signal IDs, one per element of the updated SRS resource set. Each ID in the list refers to a reference SS/PBCH block, NZP CSI-RS resource configured on serving cell indicated by Resource Serving Cell ID field in the update command if present, same serving cell as the SRS resource set otherwise, or SRS resource configured on serving cell and uplink bandwidth part indicated by Resource Serving Cell ID field and Resource BWP ID field in the update command if present, same serving cell and bandwidth part as the SRS resource set otherwise. |

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| | When the UE is configured with the higher layer parameter usage in SRS-ResourceSet set to 'antennaSwitching', the UE shall not expect to be configured with different spatial relations for SRS resources in the same SRS resource set.<br><br>The UE is not expected to be configured with different time domain behavior for SRS resources in the same SRS resource set. The UE is also not expected to be configured with different time domain behavior between SRS resource and associated SRS resources set. For operation in the same carrier, the UE is not expected to be configured on overlapping symbols with a SRS resource configured by the higher layer parameter SRS-PosResource-r16 and a SRS resource configured by the higher layer parameter SRS-Resource with resourceType of both SRS resources as 'periodic'. For operation in the same carrier, the UE is not expected to be triggered to transmit SRS on overlapping symbols with a SRS resource configured by the higher layer parameter SRS-PosResource-r16 and a SRS resource configured by the higher layer parameter SRS-Resource with resourceType of both SRS resources as 'semi-persistent' or 'aperiodic'. For operations in the same carrier, the UE is not expected to be configured on overlapping symbols with more than one SRS resources configured by the higher layer parameter SRS-PosResource-r16 with resourceType of the SRS resources as 'periodic'.<br><br>For operations in the same carrier, the UE is not expected to be triggered to transmit SRS on overlapping symbols with more than one SRS resources configured by the higher layer parameter SRS-PosResource-r16 with resourceType of the SRS resources as 'semi-persistent' or 'aperiodic'.<br><br>For intra-band and inter-band CA operations, a UE can simultaneously transmit more than one SRS resource configured by SRS-PosResource-r16 on different CCs, subject to UE's capability For intra-band and inter-band CA operations, a UE can simultaneously transmit more than one SRS resource configured by SRS-PosResource-r16 and SRS-Resource on different CCs, subject to UE's capability.<br><br>The SRS request field [5, TS38.212] in DCI format 0_1, 1_1, 0_2 (if SRS request field is present), 1_2 (if SRS request field is present) indicates the triggered SRS resource set given in Table 7.3.1.1.2-24 of [5, TS 38.212]. The 2-bit SRS request field [5, TS38.212] in DCI format 2_3 indicates the triggered SRS resource set given in Clause 7.3 of [5, TS 38.212] if the UE is |

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| | configured with higher layer parameter srs-TPC-PDCCH-Group set to 'typeB', or indicates the SRS transmission on a set of serving cells configured by higher layers if the UE is configured with higher layer parameter srs-TPC-PDCCH-Group set to 'typeA'. For PUCCH and SRS on the same carrier, a UE shall not transmit SRS when semi-persistent and periodic SRS are configured in the same symbol(s) with PUCCH carrying only CSI report(s), or only L1-RSRP report(s), or only L1-SINR report(s). A UE shall not transmit SRS when semi-persistent or periodic SRS is configured or aperiodic SRS is triggered to be transmitted in the same symbol(s) with PUCCH carrying HARQ-ACK, link recovery request (as defined in clause 9.2.4 of [6, 38.213]) and/or SR. In the case that SRS is not transmitted due to overlap with PUCCH, only the SRS symbol(s) that overlap with PUCCH symbol(s) are dropped. PUCCH shall not be transmitted when aperiodic SRS is triggered to be transmitted to overlap in the same symbol with PUCCH carrying semi-persistent/periodic CSI report(s) or semi-persistent/periodic L1-RSRP report(s) only, or only L1-SINR report(s).<br><br>In case of intra-band carrier aggregation or in inter-band CA band combination if simultaneous SRS and PUCCH/PUSCH transmissions are not supported by UE, the UE is not expected to be configured with SRS from a carrier and PUSCH/UL DM-RS/UL PT-RS/PUCCH formats from a different carrier in the same symbol. In case of intra-band carrier aggregation or in inter-band CA band combination if simultaneous SRS and PRACH transmissions are not supported by UE, the UE shall not transmit simultaneously SRS resource(s) from a carrier and PRACH from a different carrier.<br><br>In case a SRS resource with resourceType set as 'aperiodic' is triggered on the OFDM symbol(s) configured with periodic/semi-persistent SRS transmission, the UE shall transmit the aperiodic SRS resource and only the periodic/semi-persistent SRS symbol(s) overlapping within the symbol(s) are dropped, while the periodic/semi persistent SRS symbol(s) that are not overlapped with the aperiodic SRS resource are transmitted. In case a SRS resource with resourceType set as 'semi-persistent' is triggered on the OFDM symbol(s) configured with periodic SRS transmission, the UE shall transmit the semi-persistent SRS resource and only the periodic SRS symbol(s) overlapping within the symbol(s) are dropped, while the periodic SRS symbol(s) that are not overlapped with the semi-persistent SRS resource are transmitted. |

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| | When the UE is configured with the higher layer parameter usage in SRS-ResourceSet set to 'antennaSwitching', and a guard period of Y symbols is configured according to Clause 6.2.1.2, the UE shall use the same priority rules as defined above during the guard period as if SRS was configured.<br><br>When a spatialRelationInfo is activated/updated for a semi-persistent or aperiodic SRS resource configured by the higher layer parameter SRS-Resource by a MAC CE for a set of CCs/BWPs, where the applicable list of CCs is indicated by higher layer parameter simultaneousSpatial-UpdatedList-r16 or simultaneousSpatial-UpdatedListSecondr16,,the spatialRelationInfo is applied for the semi-persistent or aperiodic SRS resource(s) with the same SRS resource ID for all the BWPs in the indicated CCs.<br><br>When the higher layer parameter enableDefaultBeamPlForSRS is set 'enabled', and if the higher layer parameter spatialRelationInfo for the SRS resource, except for the SRS resource with the higher layer parameter usage in SRSResourceSet set to 'beamManagement' or for the SRS resource with the higher layer parameter usage in SRSResourceSet set to 'nonCodebook' with configuration of associatedCSI-RS or for the SRS resource configured by the higher layer parameter SRS-PosResourceSet-r16, is not configured in FR2 and if the UE is not configured with higher layer parameter(s) pathlossReferenceRS, and if the UE is not configured with different values of CORESETPoolIndex in ControlResourceSets, and is not provided at least one TCI codepoint mapped with two TCI states, the UE shall transmit the target SRS resource in an active UL BWP of a CC, - according to the spatial relation, if applicable, with a reference to the RS with 'QCL-TypeD' corresponding to the QCL assumption of the CORESET with the lowest controlResourceSetId in the active DL BWP in the CC.<br><br>- according to the spatial relation, if applicable, with a reference to the RS with 'QCL-TypeD' in the activated TCI state with the lowest ID applicable to PDSCH in the active DL BWP of the CC if the UE is not configured with any CORESET in the active DL BWP of the CC<br><br>**6.2.1.1 UE SRS frequency hopping procedure**<br><br>For a given SRS resource, the UE is configured with repetition factor R∈{1,2,4} by higher layer parameter resourceMapping in SRS-Resource where R≤Ns. When frequency hopping within an |

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| | SRS resource in each slot is not configured (R=Ns), each of the antenna ports of the SRS resource in each slot is mapped in all the Ns symbols to the same set of subcarriers in the same set of PRBs. When frequency hopping within an SRS resource in each slot is configured without repetition (R=1), according to the SRS hopping parameters BSRS , CSRS and b hop defined in Clause 6.4.1.4 of [4, TS 38.211], each of the antenna ports of the SRS resource in each slot is mapped to different sets of subcarriers in each OFDM symbol, where the same transmission comb value is assumed for different sets of subcarriers. When both frequency hopping and repetition within an SRS resource in each slot are configured (Ns=4, R=2), each of the antenna ports of the SRS resource in each slot is mapped to the same set of subcarriers within each pair of R adjacent OFDM symbols, and frequency hopping across the two pairs is according to the SRS hopping parameters $B_{SRS}$, $C_{SRS}$ and $b_{hop}$ . A UE may be configured Ns 2 or 4 = adjacent symbol aperiodic SRS resource with intra-slot frequency hopping within a bandwidth part, where the full hopping bandwidth is sounded with an equal-size subband across Ns symbols when frequency hopping is configured with R=1. A UE may be configured = 4 Ns adjacent symbols aperiodic SRS resource with intra-slot frequency hopping within a bandwidth part, where the full hopping bandwidth is sounded with an equal-size subband across two pairs of R adjacent OFDM symbols, when frequency hopping is configured with R=2. Each of the antenna ports of the SRS resource is mapped to the same set of subcarriers within each pair of R adjacent OFDM symbols of the resource. A UE may be configured Ns =1 symbol periodic or semi-persistent SRS resource with inter-slot hopping within a bandwidth part, where the SRS resource occupies the same symbol location in each slot. A UE may be configured Ns 2 or 4 = symbol periodic or semi-persistent SRS resource with intra-slot and inter-slot hopping within a bandwidth part, where the N-symbol SRS resource occupies the same symbol location(s) in each slot. For Ns=4, when frequency hopping is configured with R=2, intra-slot and inter-slot hopping is supported with each of the antenna ports of the SRS resource mapped to different sets of subcarriers across two pairs of R adjacent OFDM symbol(s) of the resource in each slot. Each of the antenna ports of the SRS resource is mapped to the same set of subcarriers within each pair of R adjacent OFDM symbols of the resource in each slot. For Ns= R, when frequency hopping is configured, inter-slot frequency hopping is supported with each of the antenna ports of the SRS resource mapped to the same set of subcarriers in R adjacent OFDM symbol(s) of the resource in each slot. |

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| | ## 6.2.1.2 UE sounding procedure for DL CSI acquisition<br><br>When the UE is configured with the higher layer parameter usage in SRS-ResourceSet set as 'antennaSwitching', the UE may be configured with only one of the following configurations depending on the indicated UE capability supportedSRS-TxPortSwitch ('t1r2' for 1T2R, 't1r1-t1r2' for 1T=1R/1T2R, 't2r4' for 2T4R, 't1r4' for 1T4R, 't1r1-t1r2-t1r4' for 1T=1R/1T2R/1T4R, 't1r4-t2r4' for 1T4R/2T4R, 't1r1-t1r2-t2r2-t2r4' for 1T=1R/1T2R/2T=2R/2T4R, 't1r1-t1r2-t2r2-t1r4-t2r4' for 1T=1R/1T2R/2T=2R/1T4R/2T4R, 't1r1' for 1T=1R, 't2r2' for 2T=2R, 't1r1-t2r2' for 1T=1R/2T=2R,'t4r4' for 4T=4R, or 't1r1-t2r2-t4r4' for 1T=1R/2T=2R/4T=4R):<br><br>- For 1T2R, up to two SRS resource sets configured with a different value for the higher layer parameter resourceType in SRS-ResourceSet set, where each set has two SRS resources transmitted in different symbols, each SRS resource in a given set consisting of a single SRS port, and the SRS port of the second resource in the set is associated with a different UE antenna port than the SRS port of the first resource in the same set, or<br><br>- For 2T4R, up to two SRS resource sets configured with a different value for the higher layer parameter resourceType in SRS-ResourceSet set, where each SRS resource set has two SRS resources transmitted in different symbols, each SRS resource in a given set consisting of two SRS ports, and the SRS port pair of the second resource is associated with a different UE antenna port pair than the SRS port pair of the first resource, or<br><br>- For 1T4R, zero or one SRS resource set configured with higher layer parameter resourceType in SRSResourceSet set to 'periodic' or 'semi-persistent' with four SRS resources transmitted in different symbols, each SRS resource in a given set consisting of a single SRS port, and the SRS port of each resource is associated with a different UE antenna port, and<br><br>- For 1T4R, zero or two SRS resource sets each configured with higher layer parameter resourceType in SRSResourceSet set to 'aperiodic' and with a total of four SRS resources transmitted in different symbols of two different slots, and where the SRS port of each SRS resource in the given two sets is associated with a different UE antenna port. The two sets are each configured with two SRS resources, or one set is configured with one SRS resource and the other set is configured with three SRS resources. The UE shall expect that the two sets are both |

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| | configured with the same values of the higher layer parameters alpha, p0, pathlossReferenceRS, and srs-PowerControlAdjustmentStates in SRS-ResourceSet. The UE shall expect that the value of the higher layer parameter aperiodicSRS-ResourceTrigger or the value of an entry in AperiodicSRS-ResourceTriggerList in each SRS-ResourceSet is the same, and the value of the higher layer parameter slotOffset in each SRS-ResourceSet is different. Or,<br><br>- For 1T=1R, or 2T=2R, or 4T=4R, up to two SRS resource sets each with one SRS resource, where the number of SRS ports for each resource is equal to 1, 2, or 4. The UE is configured with a guard period of Y symbols, in which the UE does not transmit any other signal, in the case the SRS resources of a set are transmitted in the same slot. The guard period is in-between the SRS resources of the set. The UE shall expect to be configured with the same number of SRS ports for all SRS resources in the SRS resource set(s) with higher layer parameter usage set as 'antennaSwitching'. For 1T2R, 1T4R or 2T4R, the UE shall not expect to be configured or triggered with more than one SRS resource set with higher layer parameter usage set as 'antennaSwitching' in the same slot. For 1T=1R, 2T=2R or 4T=4R, the UE shall not expect to be configured or triggered with more than one SRS resource set with higher layer parameter usage set as 'antennaSwitching' in the same symbol.<br><br>The value of Y is defined by Table 6.2.1.2-1.<br><br>6.2.1.3 UE sounding procedure between component carriers<br><br>6.2.1.4 UE sounding procedure for positioning purposes<br><br>…<br><br>*See also* 3GPP TR 38.802, 3GPP TR 38.804 v1.0.0 (2017-03), Section 5.3.4 (Beam Determination, P-1 Beam Selection), Section 10.1.2, Annex A.6<br><br>The Ericsson 5G NR RAN Solution is described as an the Ericsson Advanced Antenna Systems for 5G in the Ericsson White Paper on Advanced Antenna Systems for 5G Networks (publication, including contributors Peter von Butovitsch, David Astely, Christer Friberg, Anders Furuskär, Bo Göransson, Billy Hogan, Jonas Karlsson and Erik Larsson). The |

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| | transceiver coupled to the smart antenna and to the processor and configured to transmit the probing signal is satisfied by the active antenna system products: See https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks (also available at https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks):<br><br>See, e.g., Ericsson Advanced Antenna System for 5G Networks white paper / https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks:<br><br>***Key terms***<br>**AAS radio** = Hardware unit that comprises an antenna array, radio chains and parts of the baseband, all tightly integrated to facilitate AAS features<br>**AAS feature** = A multi-antenna feature (such as beamforming and MIMO) that can be executed in the AAS radio, in the baseband unit or both<br>**AAS** = AAS radio + AAS features<br>**Conventional system** = Passive antenna + remote radio unit comprising a low number (2, 4 or 8) of radio chains<br>**Dual-polarized antenna element** = Combination of two antenna elements with orthogonal polarizations with the purpose of enabling diversity and doubling the number of antenna elements on a given physical area<br><br>**What is an advanced antenna system?**<br>An advanced antenna system (AAS) is a combination of an AAS radio and a set of AAS features. An AAS radio consists of an antenna array closely integrated with the hardware and software required for transmission and reception of radio signals, and signal processing algorithms to support the execution of the AAS features. Compared to conventional systems, this solution provides much greater adaptivity and steerability, in terms of adapting the antenna radiation patterns to rapidly time-varying traffic and multi-path radio propagation conditions. In addition, multiple signals may be simultaneously received or transmitted with different radiation patterns. |

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| | ***Multi-antenna techniques***<br>Multi-antenna techniques, here referred to as AAS features, include beamforming and MIMO. Such features are already used with conventional systems in today's LTE networks. Applying AAS features to an AAS radio results in significant performance gains because of the higher degrees of freedom provided by the larger number of radio chains, also referred to as Massive MIMO.<br><br>**Beamforming**<br>When transmitting, beamforming is the ability to direct radio energy through the radio channel toward a specific receiver, as shown in the top left quadrant of **Figure 1**. By adjusting the phase and amplitude of the transmitted signals, constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput. Similarly, when receiving, beamforming is the ability to collect the signal energy from a specific transmitter. The beams formed by an AAS are constantly adapted to the surroundings to give high performance in both UL and DL.” |

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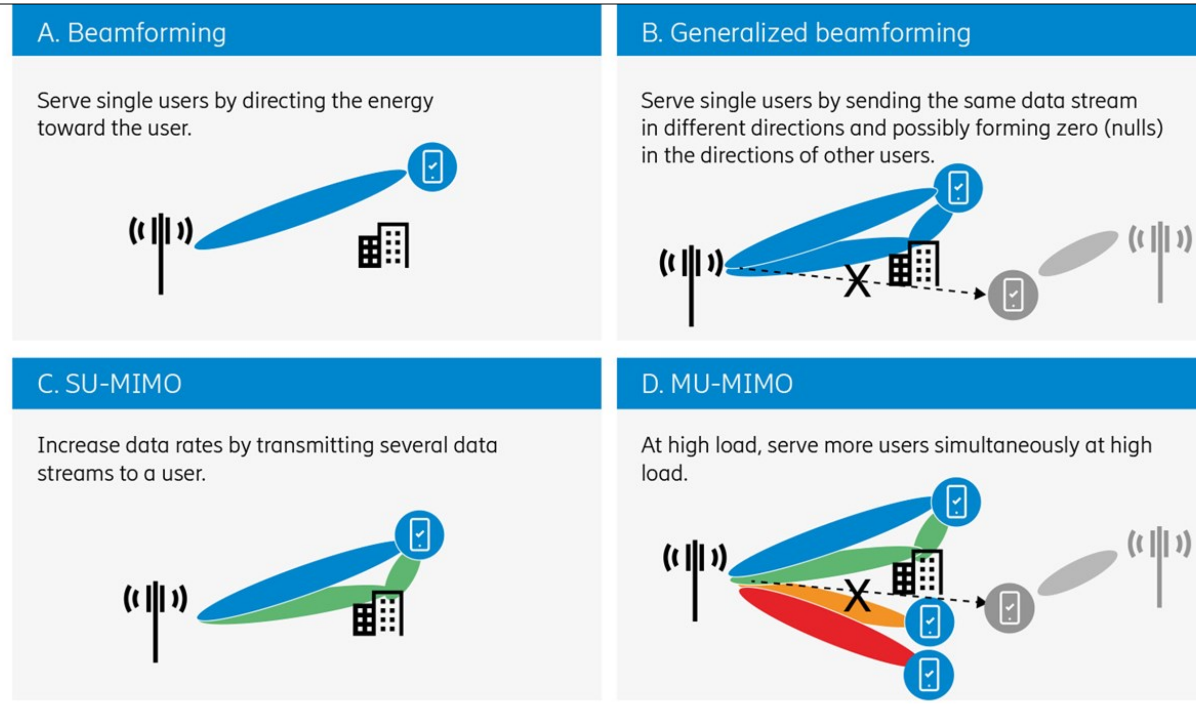
| | <br>Figure 1: Beamforming and MIMO, with the different colors of the filled beams representing streams.<br><br>Although often very effective, transmitting energy in only one direction does not always provide an optimum solution. In multi-path scenarios, where the radio channel comprises multiple propagation paths from transmitter to receiver through diffraction around corners and reflections against buildings or other objects, it is beneficial to send the same data stream in several different paths (direction and/or polarization) with phases and amplitudes controlled in a way that they add constructively at the receiver [5]. This is referred to as generalized beamforming, as shown in the upper right quadrant of Figure 1. As part of generalized beamforming, it is also possible to reduce interference to other UEs, which is known as null forming. This is achieved by |

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| | controlling the transmitted signals in a way that they cancel each other out at the interfered UEs.<br><br>**MIMO (Multiple Input, Multiple Output) techniques**<br>Spatial multiplexing, here referred to as MIMO, is the ability to transmit multiple data streams, using the same time and frequency resource, where each data stream can be beamformed. The purpose of MIMO is to increase throughput. MIMO builds on the basic principle that when the received signal quality is high, it is better to receive multiple streams of data with reduced power per stream, than one stream with full power. The potential is large when the received signal quality is high and the streams do not interfere with each other. The potential diminishes when the mutual interference between streams increases. MIMO works in both UL and DL, but for simplicity the description below will be based on the DL.<br><br>Single-user MIMO (SU-MIMO) is the ability to transmit one or multiple data streams, called layers, from one transmitting array to a single user. SU-MIMO can thereby increase the throughput for that user and increase the capacity of the network. The number of layers that can be supported, called the rank, depends on the radio channel. To distinguish between DL layers, a UE needs to have at least as many receiver antennas as there are layers.<br><br>SU-MIMO can be achieved by sending different layers on different polarizations in the same direction. SU-MIMO can also be achieved in a multi path environment, where there are many radio propagation paths of similar strength between the AAS and the UE, by sending different layers on different propagation paths, as shown in the bottom left quadrant of Figure 1.<br><br>In multi-user MIMO (MU-MIMO), which is shown in the bottom right quadrant of Figure 1, the AAS simultaneously sends different layers in separate beams to different users using the same time and frequency resource, thereby increasing the network capacity. In order to use MU-MIMO, the system needs to find two or more users that need to transmit or receive data at the very same time. Also, for efficient MU-MIMO, the |

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| | interference between the users should be kept low. This can be achieved by using generalized beamforming with null forming such that when a layer is sent to one user, nulls are formed in the directions of the other simultaneous users.<br><br>The achievable capacity gains from MU-MIMO depend on receiving each layer with good signal-to-interference-and-noise-ratio (SINR). As with SU-MIMO, the total DL power is shared between the different layers, and therefore the power (and thus SINR) for each user is reduced as the number of simultaneous MU-MIMO users increases. Also, as the number of users grows, the SINR will further deteriorate due to mutual interference between the users. Therefore, the network capacity typically improves as the number of MIMO layers increases, to a point at which power sharing and interference between users result in diminishing gains, and eventually also losses.<br><br>It should be noted that the practical benefits of many layers in MU-MIMO are limited by the fact that, in today's real networks, even with a high number of simultaneous connected users, there tends not to be many users who want to receive data simultaneously. This is due to the bursty (chatty) nature of data transmission to most users. Since the AAS and the transport network must be dimensioned for the maximum number of layers, the MNO needs to consider how many layers are required in their networks. In typical MBB deployments with the current 64T64R AAS variants, the vast majority of the DL and UL capacity gains can be achieved with up to 8 layers."<br><br>***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine |

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| | how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.<br><br>DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short- term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics.<br><br>The suitable channel knowledge scheme to use depends on UL coverage and UE capabilities. In cases where UL coverage is limiting, UE feedback offers a more robust |

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| | operation, whereas full UL channel estimation is applicable in scenarios with good coverage. In short, both reciprocity and UE feedback-based beamforming are needed.<br><br>**Antenna array structure**<br>The purpose of using a rectangular antenna array, as shown in section A of Figure 2, is to enable high-gain beams and make it possible to steer those beams over a range of angles. The gain is achieved, in both UL and DL, by constructively combining signals from a number of antenna elements. The more antenna elements there are, the higher the gain. Steerability is achieved by individually controlling the amplitude and phase of smaller parts of the antenna array. This is usually done by dividing the antenna array into so called sub-arrays (groups of non-overlapping elements), as shown in section C of Figure 2, and by applying two dedicated radio chains per sub-array (one per polarization) to enable control, as shown in section D. In this way it is possible to control the direction and other properties of the created antenna array beam. |

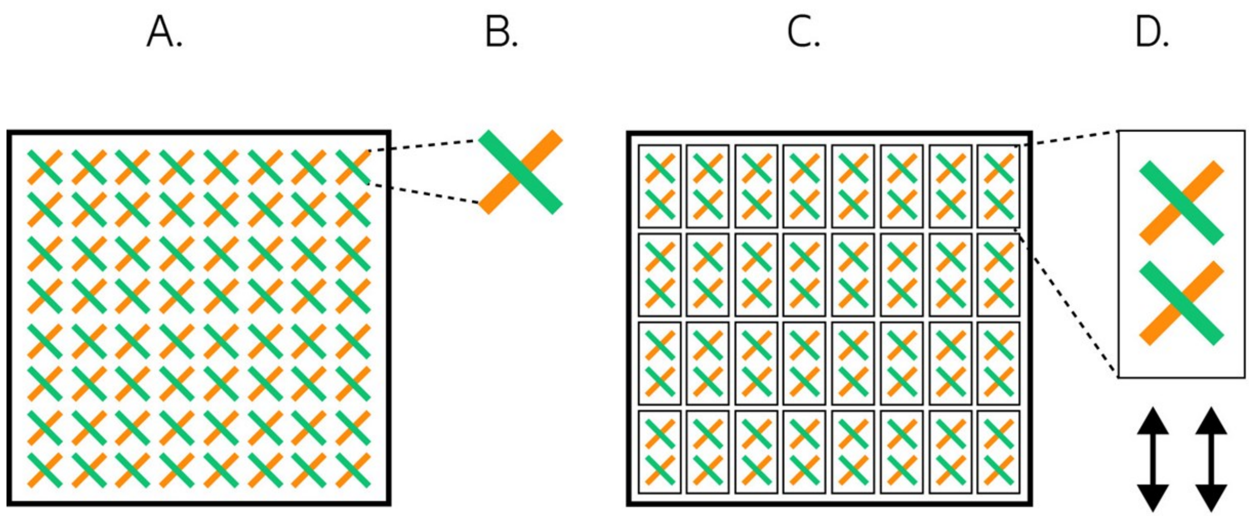


Figure 2: A typical antenna array (A) is made up of rows and columns of individual dual-polarized antenna elements (B). Antenna arrays can be divided into sub-arrays (C), with each sub-array (D) connected to two radio chains, normally one per polarization.

To see how an antenna array creates steerable high-gain beams, we start with an antenna array of a specific size, which is then divided into sub-arrays of different sizes. For illustrative purposes, we describe only one dimension. The same principles do, however, apply to both vertical and horizontal dimensions.

The array gain is referred to as the gain achieved when all sub array signals are added constructively (in phase). The size of the array gain, relative to the gain of one sub-array, depends on the number of sub-arrays – for example, two sub-arrays gives

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| | an array gain of 2 (i.e. 3 dB). By changing the phases of the sub-array signals in a certain way, this gain can be achieved in any direction, as shown in section A of Figure 3.<br><br>Each sub-array has a certain radiation pattern describing the gain in different directions. The gain and beam width depend on the size of the sub-array and the properties of the individual antenna elements. There is a trade-off between sub-array gain and beam width – the larger the sub-array, the higher the gain and the narrower the beam width, as illustrated in section B of Figure 3.<br><br>The total antenna gain is the product of the array gain and the sub-array gain, as shown in section C of Figure 3. The total number of elements determines the maximum gain and the sub-array partitioning allows steering of high gain beams over the range of angles. Moreover, the sub-array radiation pattern determines the envelope of the narrow beams (the dashed shape in section C of Figure 3). This has an implication on how to choose antenna array structure in a real deployment scenario with specific coverage requirements. Since each sub-array is normally connected to two radio chains and each radio chain is associated with a cost in terms of additional components, it is important to consider the performance benefits of additional steerability when choosing a cost-efficient array structure. |

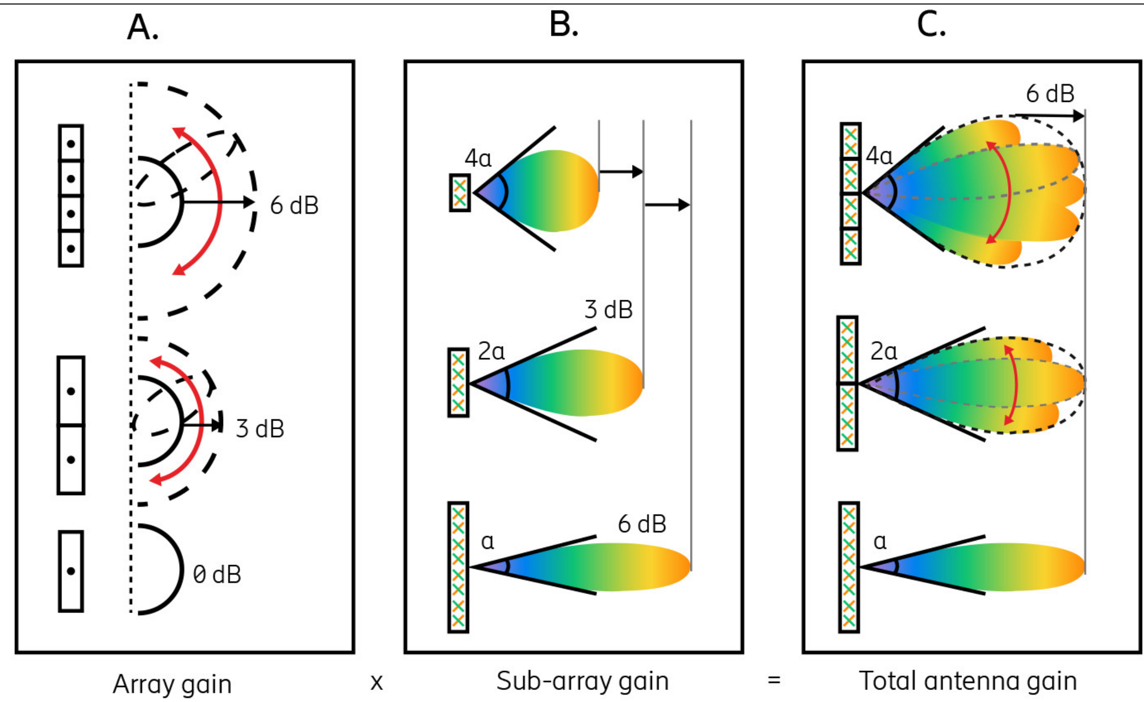


Figure 3: An array of sub-arrays supporting high total antenna gain and steerability.

**Deployment scenarios**

Determining what kind of AAS configuration is most appropriate and cost effective for a particular deployment scenario requires a mix of knowledge about the scenario, possible site constraints and available AAS features, particularly the need for vertical steerability of beams, the applicability of reciprocity-based beamforming and the gain from MU-MIMO.

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| | **Deployment scenarios**<br>Determining what kind of Massive MIMO configuration is most appropriate and cost-effective for a particular deployment scenario requires a mix of knowledge about the scenario, possible site constraints, and available Massive MIMO features, particularly the need for vertical steerability of beams, the applicability of reciprocity-based beamforming and the gain from MU-MIMO. It should be noted that horizontal beamforming is a very effective feature that provides large gains in all scenarios since the users are generally spread in the horizontal dimension. Therefore, a large number of columns is beneficial in all scenarios.<br><br>We have chosen three typical use cases to illustrate different aspects of Massive MIMO deployment: rural/suburban, urban low-rise, and dense urban high-rise. More comprehensive and practically useful recommendations can be found in[3]. The scenarios, including relevant characteristics, suitable Massive MIMO configurations, and performance potential are depicted in Figure 4. More elaborate evaluations of the performance achievable with Massive MIMO are available in reference[2] and[3]. |

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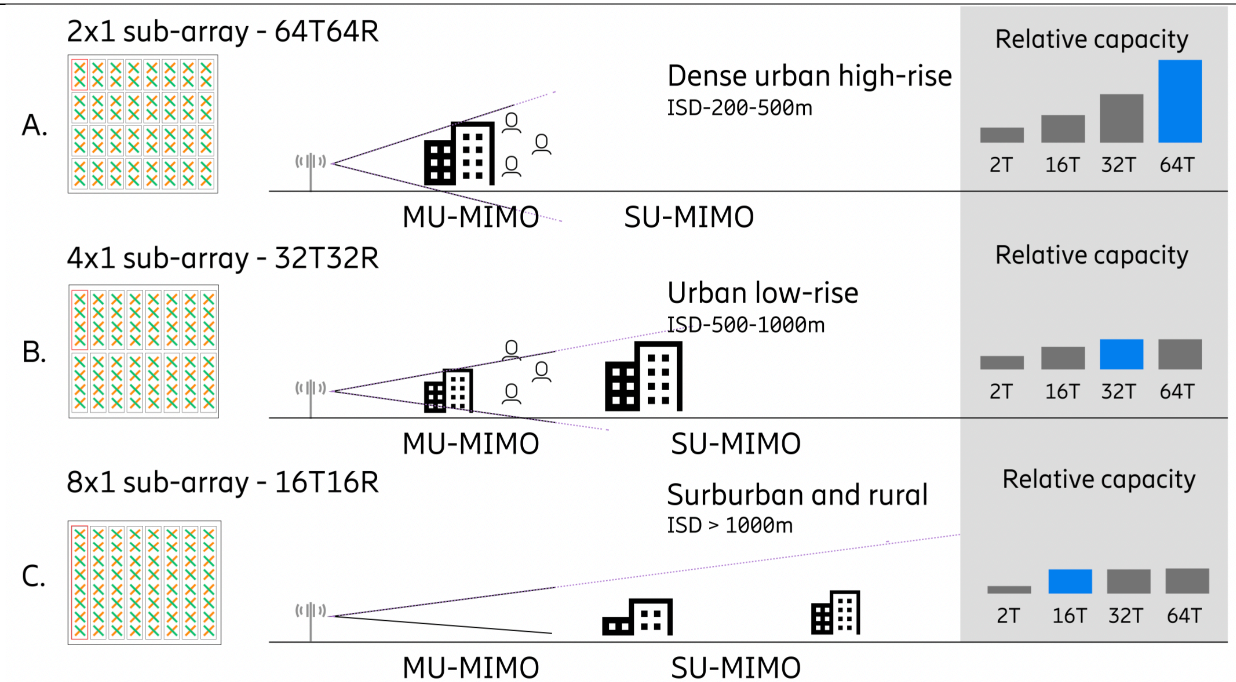
| | <br><br>Figure 4: Suitable Massive MIMO configurations, schematic MU-MIMO and SU-MIMO usage ranges, and typical capacity gains in different deployment scenarios<br><br>***Deployment scenario #1: Dense urban high-rise***<br>As depicted in section A of Figure 4, the dense urban high-rise scenario is characterized by high-rise buildings, short inter-site-distances (ISDs) of 200-500m, large traffic volume, and high subscriber density with significant user spread in the vertical dimension. The main network evolution driver has increased capacity or equivalently high end-user throughput for a given traffic load.<br><br>For conventional non-beamformed systems such as 2T2R, the vertical spread of users in combination with the small ISD creates a situation where many users are outside the vertical main beam of the nearest base station. Together with the high site density, |

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| | this leads to a situation where the signals from interfering base stations are strong, and severe interference problems may occur.<br><br>Desired Massive MIMO characteristics in the dense urban high-rise scenario include an antenna area large enough to ensure sufficient coverage (UL cell-edge data rate). Further, the vertical coverage range needs to be large enough to cover the vertical spread of users. This calls for small sub-arrays, which have a wide beam in the vertical direction. Partitioning the antenna into small vertical sub-arrays results in high-gain beams that can be steered over a large range of angles and effectively addresses the interference problems seen with conventional systems. The Massive MIMO radio needs to have a sufficient number of radio chains to support the relatively large number of sub-arrays. The good coverage and large spread of users mean that the potential for reciprocity-based beamforming and MU-MIMO with a relatively large number of multiplexed users is high, and the Massive MIMO radio should support these techniques. A good trade-off between complexity and performance could be achieved with 64 radio chains controlling small sub-arrays.<br><br>***Deployment scenario #2: Urban low-rise***<br>The urban low-rise scenario illustrated in section B of Figure 4 represents many of the larger cities around the world, including the outskirts of many high-rise cities. Base stations are typically deployed on rooftops, with inter-site distances of a few hundred meters. Compared to the dense urban high-rise scenario, traffic per area unit is lower. There is generally a mix of building types, which creates multipath propagation between the Massive MIMO radio and the UE. Maximizing the antenna area is important for improving the UL cell-edge data rates, especially for higher frequency bands employing TDD. Due to larger ISDs and decreased vertical spread of users (lower buildings), the vertical coverage range can be decreased compared to dense urban high-rises; hence, larger vertical sub-arrays can be used and there is less gain from vertical beamforming. Using larger sub-arrays for a given antenna area means that fewer radio chains are required. Reciprocity-based beamforming schemes will work for most users, but there will be users with poor coverage that need to rely on techniques such as feedback-based beamforming. MU-MIMO is also appropriate at |

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| | high loads due to the multi-path propagation environment, good link qualities, and UE pairing opportunities. A good trade-off between complexity and performance is a Massive MIMO radio with 16 to 32 radio chains.<br><br>***Deployment scenario #3: Rural/suburban***<br>Rural or suburban macro scenarios, as depicted in section C of Figure 4, are characterized by rooftop or tower-mounted base stations with inter-site distances ranging from one to several kilometers, low or medium population density and very small vertical user distribution. This scenario calls for a Massive MIMO radio with a large antenna area and the ability to support horizontal beamforming. Vertical beamforming, however, does not provide any significant gains as the vertical user spread is low. Therefore, large vertical sub-arrays with small vertical coverage areas are possible. Reciprocity-based beamforming is supported for a smaller fraction of users than in the other scenarios, and MU-MIMO gains are more limited. A good trade-off between complexity and performance is a Massive MIMO radio with 8 to 16 radio chains.<br><br>**Evolution of Massive MIMO**<br>The brief explanation of Massive MIMO above reflects the solutions in use to date (2022- Q4). The evolution of Massive MIMO is very rapid, and several tracks are being investigated to achieve higher performance. A few examples include the use of higher numbers of radio chains, larger array panels, the use of new and higher frequencies, and the use of multiple transmission points (multi-TRP). In addition to advancements in technologies specific to Massive MIMO, the use of interworking between Massive MIMO and conventional radios on other frequency bands add additional capacity beyond the sum of the two, respectively. Other developing technologies, e.g. artificial intelligence and machine learning (AI/ML) will also be applied in Massive MIMO to improve performance. Yet other technology developments, relating to for example energy performance, cost efficiency, and site deployment, are coming into use to make Massive MIMO a highly competitive and commercially viable option for mass deployment in a large variety of scenarios |

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| | Ericsson's white paper further describes deployment scenarios of Ericsson 5G NR RAN Solutions. *See id. See also* Bo Göransson, Ph.D., Ericsson, 5G – The Multi Antenna Advantage (Oct. 6, 2016), at 15, 30-32, available at http://www.1com.net/wp-content/uploads/2018/05/5G-multi-antenna-advantage.pdf<br><br>See https://www.nokia.com/networks/mobile-networks/airscale-radio-access/active-antennas/:<br><br>The AirScale active antenna portfolio includes a full range of high-performance beamforming products ensuring the most space- and energy-efficient site solutions. The portfolio supports the numerous frequency bands in use around the World as well as fulfilling operators' unique and varied deployment needs.<br><br>**Massive MIMO Adaptive Antennas**<br><br>Our AirScale massive MIMO Adaptive Antennas portfolio includes 32TRX and 64TRX for the TDD 4G and 5G mid-bands and dual-band 16TRX for FDD bands. Each enabling the deployment of beamforming optimized solutions covering all deployment scenarios, from dense-urban capacity to wide-area coverage<br><br>**New generation Massive MIMO Adaptive Antennas**<br><br>Our AirScale massive MIMO Adaptive Antennas portfolio includes 32TRX and 64TRX for the TDD 4G and 5G mid-bands and dual-band 16TRX for FDD bands. These enable the deployment of beamforming optimized solutions |

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| | covering all deployment scenarios, from dense-urban capacity to wide-area coverage.<br><br>Powered by Nokia new generation ReefShark System on Chip (SoC), these new generation massive MIMO antennas are light in weight and industry leading at 17 kilograms. This simplifies deployment considerations and eases installation, speeding-up the rollout of 5G.<br><br>These new designs also support high RF bandwidths, up to 400 MHz, making them ideal for covering fragmented spectrum or network sharing use cases. The ability to support high bandwidth can mean the difference between deploying one or multiple antennas.<br><br>Available in both 32TRX and 64TRX configurations, these industry leading antennas are the ideal choice for all 5G network deployments, delivering high-performance and high-efficiency, while also simplifying site solutions. |

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| | **New 32TRX massive MIMO antennas**<br>Industry leading solutions, supporting both 400 MHz RF bandwidth and the lightest weight, 17kg<br><br>**New 64TRX massive MIMO antennas**<br>400 MHz RF bandwidth and high power for maximum capacity and coverage<br><br>**Powered by new generation Nokia ReefShark SoCs**<br>The foundation for high RF bandwidth and high performance<br><br> |

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| 1[b] determining at least one forward path pre-equalization parameter based on said at least one transmission delay; and | Each accused product performs a method 1[b] determining at least one forward path pre-equalization parameter based on said at least one transmission delay. All evidence and document excerpts for 1[a] are expressly incorporated by reference here.<br><br>For a first example, as explained above, the accused products/instrumentalities identify at least one multipath transmission delay within a reverse path data signal received from a receiving device corresponding to a user equipment device. As an example, the Nokia or Ericsson RAN solution includes at least a gNB base station that communicates with user equipment devices. The gNB is configured to receive a Sounding Reference Signal (SRS) when the user equipment device transmits a Sounding Reference Signal (SRS) ("reverse path data signal"). The gNB uses the SRS transmitted by the user equipment device to e.g. estimate the channel (e.g., channel frequency response, channel impulse response, estimated phase offset, estimated amplitude offset) ("identifying at least one multipath transmission delay") on at least a subset of the frequency tones.<br><br>In an example relating to SRS, the base station elicits Sounding Reference Signals from the UE mobile device. For example, the base station can configure multiple antenna ports for SRS. For example, the UE can transmit SRSs using one or multiple antenna elements and one or multiple layers / streams and the base station can receive SRSs via one or more antenna elements. For example, the base station receives SRS using different beams and/or layers and/or antenna. Once the gNB receives SRSs, it processes the received SRSs to determine information about the channel and identify multipath transmission delay. For example, channel estimation using received SRS can be used for DL or UL precoding and beamforming. For example, channel estimation procedures using received SRS can be used to determine precoding and/or PMI to be used for DL or UL. The base station transmits signals to the UE with precoding that is determined using channel estimation. The base station processes the received SRS to determine information about the channel and to identify a multipath transmission delay within the reverse path data signal from the UE, and to determine how to modify a forward path data signal that is to be transmitted to the UE by determining precoding that adjusts transmit power on at least two OFDM tones, through the 5G NR beamforming functionalities, such as for TDD.<br><br>In TDD systems, the multipath transmission delay identified by the gNB, using the received SRS symbols, is, by taking advantage of channel reciprocity property of a TDD system, used by |

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| | the gNB to compute a set of beamforming coefficient parameters ("pre-equalization parameter") that are used for precoding, much like PMI parameters in FDD systems. These pre-equalization parameters are, as in PMI approach, applied to the data stream to form a downlink beam. For example, in a TDD system (where UL and DL channels are considered reciprocal), Ericsson and/or Nokia base stations calculate DL precoding weights based on the sounding reference signal that a user transmits in UL.<br><br>As another example, the base station also supports identifying multipath transmission delays in signals from reverse path data signals from the UEs. See, e.g., Ericsson White Paper entitled "Massive MIMO for 5G networks," available at https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks ("To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station."). For example, the cellular base station sends a CSI-RS signal to the connected UE mobile devices, and the UEs then measure and report back channel state information as feedback to the cellular base station. For example, CSI-RS is a standardized aspect of 5G NR that requires base stations to generate CSI-RS signals for transmission and then the UEs respond to the CSI-RS reference signal with CSI feedback to the base station. The CSI feedback can be sent, for example, using multiple layers or streams and multiple antennas on, e.g., PUSCH with data and e.g. on PUCCH. As an example, see the descriptions for Type I & II Codebook and Enhanced Type II codebook for e.g. 1-layer and 2-layer CSI reporting in 3GPP TS 38.214 § 5.2.2 and § 6. The base station processes the received CSI feedback signals ("reverse path data signal") to determine information about the channel and to identify a "multipath transmission delay" within the reverse path data signal, and to determine how to modify a forward path data signal that is to be transmitted to the UE by determining precoding that adjusts transmit power levels on at least two OFDM tones. As an example, the base station determines a Type II or Enhanced Type II precoding matrix and determines layer configuration and precoding for beamforming transmissions to UE, and this process corresponds to determining forward path pre-equalization parameter based on the transmission delay, and modifying a forward path data signal that is to be transmitted to the UE by setting different transmit power levels for at least two OFDM tones in the forward path data signal. For example, in downlink beamforming in FDD systems, the gNB base station expects that the user equipment device makes Channel State Information (CSI) measurements such as |

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| | the Precoding Matrix Indicator (PMI) and transmits the PMI to the gNB. The gNB receives CSI measurements such as PMI in a reverse path data signal received from the user equipment device. The gNB identifies at least one multipath transmission delay in the reverse path data signal. The gNB determines at least one forward path pre-equalization parameter based on the transmission delay. For example, PMI is an index to a set of coefficients ("forward path pre-equalization parameter") that are applied to the data stream to e.g. form a beam toward the device. The base station determines the DL precoding weights / coefficients to apply based on the identified multipath transmission delay.<br><br>For example, in downlink beamforming in FDD systems, the gNB base station expects that the user equipment device makes Channel State Information (CSI) measurements such as the Precoding Matrix Indicator (PMI) and transmits the PMI to the gNB. The gNB receives the CSI measurements such as PMI in a reverse path data signal received from the user equipment device. The gNB identifies at least one multipath transmission delay in the reverse path data signal. The gNB determines at least one forward path pre-equalization parameter based on the transmission delay. For example, PMI is an index to a set of precoding coefficients ("forward path pre-equalization parameter") that are applied to the data stream to e.g. form a beam toward the device. The base station determines the DL precoding weights / coefficients to apply based on the identified multipath transmission delay. For example, Ericsson and/or Nokia base stations calculate DL precoding weights based on the multipath transmission delay.<br><br>As yet another example, the Ericsson and/or Nokia RAN Solutions may use analog beamforming or combination of analog and digital beamforming. For example, the RAN Solution also identifies at least one multipath transmission delay in a reverse path data signal when determining antenna array element coefficients by evaluating signals received on the elements of the array. The base station determines at least one forward path pre-equalization parameter (e.g., analog domain and digital domain coefficients / complex numbers (e.g., amplitude, phase) channel parameters, e.g., for beamforming or MIMO, that are applied to downlink transmission signals) based on identifying the multipath transmission delay. These forward path pre-equalization parameters (e.g., analog domain and digital domain coefficients / complex numbers (e.g., amplitude, phase) channel parameters, e.g., for beamforming or MIMO, that are applied to downlink transmission signals) selectively set different transmission power levels for at least two OFDM tones. |

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| | Claim limitation 1[b] is literally infringed by each Accused Product. However, to the extent claim limitation 1[b] is not met literally, it is nonetheless met under the doctrine of equivalents because the differences between the claim limitation and each Accused Product would be insubstantial, and each Accused Product performs substantially the same function, in substantially the same way, to achieve the same result as the claimed invention. For example, DL precoding as described herein is literally the same as and/or is insubstantially different from forward path pre-equalization parameter and performs substantially the same function in substantially the same way (DL precoding) to achieve substantially the same result (beamforming parameters that ameliorate multipath effects). For a further example, the doctrine of equivalents theories for 1[a] and 1[c] are incorporated by reference herein to the extent they also relate to terms recited in 1[b], and vice versa. Thus, as explained for 1[a], for example, channel estimation on SRS or identifying PMI in a reverse path data signal from the UE performs substantially the same function of determining and identifying at least one multipath transmission delay in substantially the same way of determining the multipath channel response from uplink transmission to achieve substantially the same result of computing forward path pre-equalization parameters. The channel estimation techniques used to identify multipath transmission delay parameters using SRS or PMI (e.g., enhanced Type II codebook), including, e.g., beam angles, complex numbers, is substantially the same way as identifying at least one multipath transmission delay within a reverse path data signal. Likewise, DL beamforming precoding / beamforming coefficients for downlink transmissions that the base station selects based on the channel estimation described for 1[a] is performing substantially the same function of determining and identifying at least one multipath transmission delay and determining pre-equalization parameters for downlink based on that in substantially the same way of determining the multipath channel response from uplink transmission using SRS or PMI and determining the downlink beamforming precoding based on that to achieve substantially the same result of computing forward path pre-equalization parameters that ameliorate multipath effects. As another example, determining channel estimation, including complex numbers, phase offset between e.g. the known/reference SRS and the received multipath SRS is substantially the same way as identifying multipath transmission delay, including because this determination is caused by and directly linear proportional to multipath transmission delay between the known/reference SRS and received multipath SRS and is for substantially the same purpose of understanding the multipath effects on the received multipath SRS and determining pre-equalization parameters accordingly. As another example, determining channel estimation, including complex numbers, |

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| | phase offset between e.g. the known/reference CSI-RS and the received multipath CSI-RS, and identifying CSI and PMI that is computed based on the difference between the CSI-RS and the received CSI-RS, is substantially the same way, including because this determination is caused by and directly linear proportional to multipath transmission delay between the known/reference CSI-RS and received multipath CSI-RS and is for substantially the same purpose of understanding the multipath effects on the signal and determining forward path pre-equalization parameters based on the multipath. The result is substantially the same. The result is a channel estimate that conveys the multipath propagation delay characteristics of the channel. The channel estimate is used to determine downlink beamforming precoding generating simultaneous beams in a multipath environment where the downlink beamforming precoding parameters (pre-equalization parameters) are selectively adjusted in e.g. phase and amplitude to produce a signal at the user equipment that has ameliorated multipath propagation effects.<br><br>See Ericsson White Paper entitled Massive MIMO for 5G Networks," dated Feb. 2023:<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by a suitable averaging of UL channel estimate statistics.<br><br>See 3GPP TS 38.214 V15.6.0 (2019-06): |

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## 5.2 UE procedure for reporting channel state information (CSI)

### 5.2.1 Channel state information framework

The time and frequency resources that can be used by the UE to report CSI are controlled by the gNB. CSI may consist of Channel Quality Indicator (CQI), precoding matrix indicator (PMI), CSI-RS resource indicator (CRI), SS/PBCH Block Resource indicator (SSBRI), layer indicator (LI), rank indicator (RI) and/or L1-RSRP.

For CQI, PMI, CRI, SSBRI, LI, RI, L1-RSRP, a UE is configured by higher layers with N≥1 *CSI-ReportConfig* Reporting Settings, M≥1 *CSI-ResourceConfig* Resource Settings, and one or two list(s) of trigger states (given by the higher layer parameters *CSI-AperiodicTriggerStateList* and *CSI-SemiPersistentOnPUSCH-TriggerStateList*). Each trigger state in *CSI-AperiodicTriggerStateList* contains a list of associated *CSI-ReportConfigs* indicating the Resource Set IDs for channel and optionally for interference. Each trigger state in *CSI-SemiPersistentOnPUSCH-TriggerStateList* contains one associated *CSI-ReportConfig*.

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*5.2.2.2 Precoding matrix indicator (PMI)*

#### 5.2.2.2.1 Type I Single-Panel Codebook

For 2 antenna ports {3000, 3001} and the UE configured with higher layer parameter *codebookType* set to 'typeI-SinglePanel' each PMI value corresponds to a codebook index given in Table 5.2.2.2.1-1. The UE is configured with the higher layer parameter *twoTX-CodebookSubsetRestriction*. The bitmap parameter *twoTX-CodebookSubsetRestriction* forms the bit sequence $a_5,...,a_1,a_0$ where $a_0$ is the LSB and $a_5$ is the MSB and where a bit value of zero indicates that PMI reporting is not allowed to correspond to the precoder associated with the bit. Bits 0 to 3 are associated respectively with the codebook indices 0 to 3 for $\upsilon=1$ layer, and bits 4 and 5 are associated respectively with the codebook indices 0 and 1 for $\upsilon=2$ layers.

**Table 5.2.2.2.1-1: Codebooks for 1-layer and 2-layer CSI reporting using antenna ports 3000 to 3001**

| Codebook index | Number of layers $\upsilon$ | |
|---|---|---|
| | **1** | **2** |
| **0** | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$ |

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| | **1** | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$ |
| | **2** | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$ | - |
| | **3** | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$ | - |

For 4 antenna ports {3000, 3001, 3002, 3003}, 8 antenna ports {3000, 3001, …, 3007}, 12 antenna ports {3000, 3001, …, 3011}, 16 antenna ports {3000, 3001, …, 3015}, 24 antenna ports {3000, 3001, …, 3023}, and 32 antenna ports {3000, 3001, …, 3031}, and the UE configured with higher layer parameter *codebookType* set to 'typeI-SinglePanel', except when the number of layers $\upsilon \in \{2,3,4\}$ (where $\upsilon$ is the associated RI value), each PMI value corresponds to three codebook indices $i_{1,1}, i_{1,2}, i_2$. When the number of layers $\upsilon \in \{2,3,4\}$, each PMI value corresponds to four codebook indices $i_{1,1}, i_{1,2}, i_{1,3}, i_2$. The composite codebook index $i_1$ is defined by

$$i_1 = \begin{cases} \begin{bmatrix} i_{1,1} & i_{1,2} \end{bmatrix} & \upsilon \notin \{2,3,4\} \\ \begin{bmatrix} i_{1,1} & i_{1,2} & i_{1,3} \end{bmatrix} & \upsilon \in \{2,3,4\} \end{cases}$$

The codebooks for 1-8 layers are given respectively in Tables 5.2.2.2.1-5, 5.2.2.2.1-6, 5.2.2.2.1-7, 5.2.2.2.1-8, 5.2.2.2.1-9, 5.2.2.2.1-10, 5.2.2.2.1-11, and 5.2.2.2.1-12. The mapping from $i_{1,3}$ to $k_1$ and $k_2$ for 2-layer reporting is given in Table 5.2.2.2.1-3. The mapping from $i_{1,3}$ to $k_1$ and $k_2$ for 3-layer and 4-layer reporting when $P_{\text{CSI-RS}} < 16$ is given in Table 5.2.2.2.1-4. The quantities $\varphi_n$, $\theta_p$, $u_m$, $v_{l,m}$, and $\tilde{v}_{l,m}$ are given by

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| | $$\varphi_n = e^{j\pi n/2}$$ $$\theta_p = e^{j\pi p/4}$$ $$u_m = \begin{cases} \begin{bmatrix} 1 & e^{j\frac{2\pi m}{O_2 N_2}} & \cdots & e^{j\frac{2\pi m(N_2-1)}{O_2 N_2}} \end{bmatrix} & N_2 > 1 \\ 1 & N_2 = 1 \end{cases}$$ $$v_{l,m} = \begin{bmatrix} u_m & e^{j\frac{2\pi l}{O_1 N_1}} u_m & \cdots & e^{j\frac{2\pi l(N_1-1)}{O_1 N_1}} u_m \end{bmatrix}^T$$ $$\tilde{v}_{l,m} = \begin{bmatrix} u_m & e^{j\frac{4\pi l}{O_1 N_1}} u_m & \cdots & e^{j\frac{4\pi l(N_1/2-1)}{O_1 N_1}} u_m \end{bmatrix}^T$$ - The values of $N_1$ and $N_2$ are configured with the higher layer parameter *n1-n2*, respectively. The supported configurations of $(N_1, N_2)$ for a given number of CSI-RS ports and the corresponding values of $(O_1, O_2)$ are given in Table 5.2.2.2.1-2. The number of CSI-RS ports, $P_{\text{CSI-RS}}$, is $2N_1N_2$.<br>- UE shall only use $i_{1,2} = 0$ and shall not report $i_{1,2}$ if the value of $N_2$ is 1.<br><br>See also 5.2.2.2.2 (Type I Port Selection), 5.2.2.2.3 (Type II), 5.2.2.2.4 (Type II Port Selection), 5.2.2.2.5 (Enhanced Type II), 5.2.2.2.6 (Enhanced Type II Port Selection).<br><br>See additional evidence cited in chart above which is expressly incorporated by reference here.<br><br>See Ericsson White Paper entitled "Massive MIMO for 5G networks," updated Feb. 2023: (available at https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks): |

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| | ***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.<br><br>DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE |

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| | antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics.<br><br>See https://www.techplayon.com/nr-sound-reference-signal-nr-srs/:<br><br>**5G NR Sounding Reference Signal (NR-SRS)**<br><br>In NR there are two types of Reference Signal in UL which gives information about the channel quality.<br><br>1. DMRS:- Demodulation Reference Signal<br>2. SRS:- Sounding Reference Signal<br><br>With the help of above two RS, gNB takes smart decisions for resource allocation for uplink transmission, link adaptation and to decode transmitted data from UE. SRS is a UL reference signal which is transmitted by UE to Base station. SRS gives information about the combined effect of multipath fading, scattering, Doppler and power loss of transmitted signal.<br><br>Hence Base Station estimates the channel quality using this reference signal and manages further resource scheduling, Beam management, and power control of signal. So SRS provides information to gNB about the channel over full bandwidth and using this information gNB takes decision for resource allocation which has better channel quality comparing to other Bandwidth regions.<br><br>See 3GPP TS 38.214 version 15.16.0 (2022-03):<br><br>6.2 UE reference signal (RS) procedure<br>6.2.1 UE sounding procedure<br>The UE may be configured with one or more Sounding Reference Signal (SRS) resource sets as configured by the higher layer parameter *SRS-ResourceSet*. For each SRS resource set, a UE |

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| | may be configured with $K \geq 1$ SRS resources (higher layer parameter *SRS-Resource*), where the maximum value of K is indicated by UE capability [13, 38.306]. The SRS resource set applicability is configured by the higher layer parameter *usage* in *SRS-ResourceSet.* When the higher layer parameter *usage* is set to 'beamManagement'*,* only one SRS resource in each of multiple SRS sets may be transmitted at a given time instant, but the SRS resources in different SRS resource sets with the same time domain behaviour in the same BWP may be transmitted simultaneously.<br>For aperiodic SRS at least one state of the DCI field is used to select at least one out of the configured SRS resource set(s).<br>The following SRS parameters are semi-statically configurable by higher layer parameter *SRS-Resource*.<br>- *srs-ResourceId* determines SRS resource configuration identity.<br>- Number of SRS ports as defined by the higher layer parameter *nrofSRS-Ports* and described in Subclause 6.4.1.4 of [4, TS 38.211].<br>- Time domain behaviour of SRS resource configuration as indicated by the higher layer parameter *resourceType*, which may be periodic, semi-persistent, aperiodic SRS transmission as defined in Subclause 6.4.1.4 of [4, TS 38.211].<br>- Slot level periodicity and slot level offset as defined by the higher layer parameters *periodicityAndOffset-p* or *periodicityAndOffset-sp* for an SRS resource of type periodic or semi-persistent. The UE is not expected to be configured with SRS resources in the same SRS resource set *SRS-ResourceSet* with different slot level periodicities. For an *SRS-ResourceSet* configured with higher layer parameter *resourceType* set to 'aperiodic', a slot level offset is defined by the higher layer parameter *slotOffset*.<br>- Number of OFDM symbols in the SRS resource, starting OFDM symbol of the SRS resource within a slot including repetition factor R as defined by the higher layer parameter *resourceMapping* and described in Subclause 6.4.1.4 of [4, TS 38.211].<br>- SRS bandwidth $B_{SRS}$ and $C_{SRS}$, as defined by the higher layer parameter *freqHopping* and described in Subclause 6.4.1.4 of [4, TS 38.211].<br>- Frequency hopping bandwidth, $b_{hop}$, as defined by the higher layer parameter *freqHopping* and described in Subclause 6.4.1.4 of [4, TS 38.211]. |

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| | - Defining frequency domain position and configurable shift, as defined by the higher layer parameters *freqDomainPosition* and *freqDomainShift, respectively,* and described in Subclause 6.4.1.4 of [4, TS 38.211].<br><br>See 3GPP TS 38.211 v15.6.0 (2019-06):<br><br>*6.4.1.4 Sounding reference signal*<br>6.4.1.4.1 SRS resource<br>An SRS resource is configured by the *SRS-Resource* IE and consists of<br>- $N_{\text{ap}}^{\text{SRS}} \in \{1,2,4\}$ antenna ports $\{p_i\}_{i=0}^{N_{\text{ap}}^{\text{SRS}}-1}$, where the number of antenna ports is given by the higher layer parameter *nrofSRS-Ports*, $p_i = 1000 + i$ when the SRS resource is in a SRS resource set with higher-layer parameter *usage* in *SRS-ResourceSet* not set to 'nonCodebook', or determined according to [6, TS 38.214] when the SRS resource is in a SRS resource set with higher-layer parameter *usage* in *SRS-ResourceSet* set to 'nonCodebook'<br>- $N_{\text{symb}}^{\text{SRS}} \in \{1,2,4\}$ consecutive OFDM symbols given by the field *nrofSymbols* contained in the higher layer parameter *resourceMapping*<br>- $l_0$, the starting position in the time domain given by $l_0 = N_{\text{symb}}^{\text{slot}} - 1 - l_{\text{offset}}$ where the offset $l_{\text{offset}} \in \{0,1,\ldots,5\}$counts symbols backwards from the end of the slot and is given by the field *startPosition* contained in the higher layer parameter *resourceMapping* and $l_{\text{offset}} \geq N_{\text{symb}}^{\text{SRS}} - 1$<br>- $k_0$, the frequency-domain starting position of the sounding reference signal<br><br>Each accused product performs a method determining at least one forward path pre-equalization parameter based on said at least one transmission delay.<br><br>For example, TDD systems, the multipath transmission delay identified by the gNB using the received SRS symbols, is, by taking advantage of channel reciprocity property of a TDD system, used by the gNB to compute a set of beamforming coefficient parameters ("pre-equalization parameter") that are used for precoding, much like PMI parameters in e.g. FDD systems. These pre-equalization parameters are, as in the PMI approach, applied to the data stream to form a downlink beam. For example, in a TDD system (where UL and DL channels |

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| | are considered reciprocal), an Ericsson and/or Nokia base station calculates DL precoding weights based on the sounding reference signal that a user transmits in UL.<br><br>For example, the base station may compare the received SRS signal with a local version that is a known SRS reference signal to estimate the channel (e.g., channel multipath delay profile) using, e.g., correlation techniques.<br><br>https://www.sharetechnote.com/html/5G/5G_SRS.html<br><br>**Phase I** - RRC Configuration for SRS<br>This is the phase where gNB determines about SRS configuration (e.g., SRS physical resources, usage, report period timing etc.) and notifies the configuration to UE via RRC messages (e.g., RRCSetup, RRCReconfiguration).<br>**Phase II** - SRS transmission from UE:<br>In this phase, the UE transmits the SRS, which is a predefined signal with known characteristics, at a specific time and frequency. The SRS configuration is provided to the UE by the gNB, and it may vary depending on the cell's conditions and traffic requirements. The UE sends the SRS periodically or aperiodically, as instructed by the gNB, on the uplink (UL) channel.<br>**NOTE** : gNB can configure UE to transmit the srs across the full band at once or can configure UE to transmit the srs for a certain segment of the frequency band using the parameter explained in Bandwidth Configuration.<br>**NOTE** : gNB configures how often and at which timing UE should send SRS. gNB would get better and more accurate information as it let UE to transmit more often for wider frequency span, but overhead caused by srs transmission would get higher.<br>**Phase III** - SRS reception at gNB and Analysis:<br>Upon receiving the SRS from the UE, the gNB measures and analyzes the received signal. It estimates the channel state information (CSI) by comparing the received SRS with the known reference signal. The gNB evaluates various parameters, such as the path loss, propagation delay(phase delay), and received signal strength, to understand the current radio environment and channel conditions between the gNB and the UE.<br><br>https://telcomaglobal.com/p/5g-nr-srs-sounding-reference-signals<br><br>**5G NR SRS (Sounding Reference Signals)**<br>Introduction<br><br>SRS is Sounding Reference Signal is a reference signal transmitted by the UE in the uplink direction which is used by the eNodeB to estimate the uplink channel quality over a wider bandwidth. SRS is a UL |

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| | reference signal which is transmitted by UE to the base station. SRS gives information about the combined effect of multipath fading, scattering, Doppler, and power loss of the transmitted signal. Sounding reference signals are uplink physical signals employed by user equipment (UE) for uplink channel sounding, including channel quality estimation and synchronization. Unlike Demodulation reference signals (DM-RS), SRS is not associated with any physical uplink channels, and they support uplink channel-dependent scheduling and link adaptation. SRS assist in:<br>• Codebook-based closed-loop spatial multiplexing<br>• Control uplink transmit timing<br>• Reciprocity-based downlink precoding in multi-user MIMO setups<br>• Quasi co-location of physical channels and reference signals<br>In 5G NR, the SRS is transmitted by the UE for uplink channel sounding, which includes channel estimation and synchronization. An NR-SRS is an uplink orthogonal frequency division multiplexing (OFDM) signal filled with a Zadoff-Chu sequence on different subcarriers. For the purposes of communications, the SRS is used for closed-loop spatial multiplexing, uplink transmitting timing control, and reciprocity multi-user downlink precoding. To utilize the channel sounding function, the SRS must be known by both the UE and the gNB. UE act as a mobile transmitter and gNB act as a base station receiver.<br>Base station estimates the channel quality using this reference signal and manages further resource scheduling, Beam management, and power control of the signal. So SRS provides information to gNB about the channel over the full bandwidth and using this information, gNB takes decisions for resource allocation which has better channel quality as compared to other Bandwidth regions<br><br>https://www.mathworks.com/help/5g/ug/tdd-reciprocity-based-pdsch-beamforming-using-srs.html<br>**TDD Reciprocity-Based PDSCH MU-MIMO Using SRS**<br>This example implements downlink multiuser multiple-input multiple-output (MU-MIMO) by exploiting channel reciprocity in a time division duplex (TDD) scenario. The example shows how to determine beamforming weights for physical downlink shared channel (PDSCH) transmission by using channel estimates based on uplink sounding reference signals (SRS) |

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| | transmitted for each user, and how to schedule PDSCHs for multiple users in the same time and frequency resources.<br>**Introduction**<br>TDD systems use the same frequency band for uplink (UL) and downlink (DL) transmissions. The radio channel is reciprocal because it has the same characteristics in both UL and DL directions. Exploiting this reciprocity, you can use a UL transmission to obtain a channel estimate and then use this channel estimate to calculate parameters, including beamforming, for a DL transmission. This method is known as reciprocity-based beamforming.<br>This example implements downlink MU-MIMO by calculating a channel estimate for multiple users based on their SRS transmissions. Assuming reciprocity, the example then uses these channel estimates to select a set of users to be scheduled for PDSCH transmission and calculates DL beamforming weights for PDSCH transmissions to those users. When the base station has a sufficient number of antennas, it is possible to beamform PDSCH transmissions for a set of users in the same time and frequency resources such that the users suffer little interference from each other.<br>This example schedules SRS transmissions for all UEs in the UL part of the special slot, and schedules PDSCH transmissions for UEs chosen by the user selection algorithm in DL slots and the DL part of special slots.<br>* * *<br>As another example, in downlink beamforming in e.g. FDD systems, the Ericsson and/or Nokia gNB base station expects that the user equipment device makes Channel State Information (CSI) measurements such as the Precoding Matrix Indicator (PMI) and transmits the PMI to the gNB. The gNB receives the CSI measurements such as PMI in a reverse path data signal received from the user equipment device. The gNB identifies at least one multipath transmission delay in the reverse path data signal (e.g., the CSI measurements such as, e.g., PMI). The gNB determines at least one forward path pre-equalization parameter based on the transmission delay. For example, PMI is an index to a set of coefficients (“forward path pre-equalization parameter”) that are applied to the data stream to e.g. form a beam toward the device. The base station determines the DL precoding weights / coefficients to apply based on the identified multipath transmission delay. |

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| | See Ericsson White Paper entitled Massive MIMO for 5G Networks," dated Feb. 2023:<br><br>See, e.g., Ericsson Advanced Antenna System for 5G Networks white paper / https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks:<br><br>***Key terms***<br>**AAS radio** = Hardware unit that comprises an antenna array, radio chains and parts of the baseband, all tightly integrated to facilitate AAS features<br>**AAS feature** = A multi-antenna feature (such as beamforming and MIMO) that can be executed in the AAS radio, in the baseband unit or both<br>**AAS** = AAS radio + AAS features<br>**Conventional system** = Passive antenna + remote radio unit comprising a low number (2, 4 or 8) of radio chains<br>**Dual-polarized antenna element** = Combination of two antenna elements with orthogonal polarizations with the purpose of enabling diversity and doubling the number of antenna elements on a given physical area<br><br>**What is an advanced antenna system?**<br>An advanced antenna system (AAS) is a combination of an AAS radio and a set of AAS features. An AAS radio consists of an antenna array closely integrated with the hardware and software required for transmission and reception of radio signals, and signal processing algorithms to support the execution of the AAS features. Compared to conventional systems, this solution provides much greater adaptivity and steerability, in terms of adapting the antenna radiation patterns to rapidly time-varying traffic and multi-path radio propagation conditions. In addition, multiple signals may be simultaneously received or transmitted with different radiation patterns.<br><br>***Multi-antenna techniques***<br>Multi-antenna techniques, here referred to as AAS features, include beamforming and MIMO. Such features are already used with conventional systems in today's LTE networks. Applying AAS features to an AAS radio results in significant performance |

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| | gains because of the higher degrees of freedom provided by the larger number of radio chains, also referred to as Massive MIMO.<br><br>**Beamforming**<br>When transmitting, beamforming is the ability to direct radio energy through the radio channel toward a specific receiver, as shown in the top left quadrant of **Figure 1**. By adjusting the phase and amplitude of the transmitted signals, constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput. Similarly, when receiving, beamforming is the ability to collect the signal energy from a specific transmitter. The beams formed by an AAS are constantly adapted to the surroundings to give high performance in both UL and DL." |

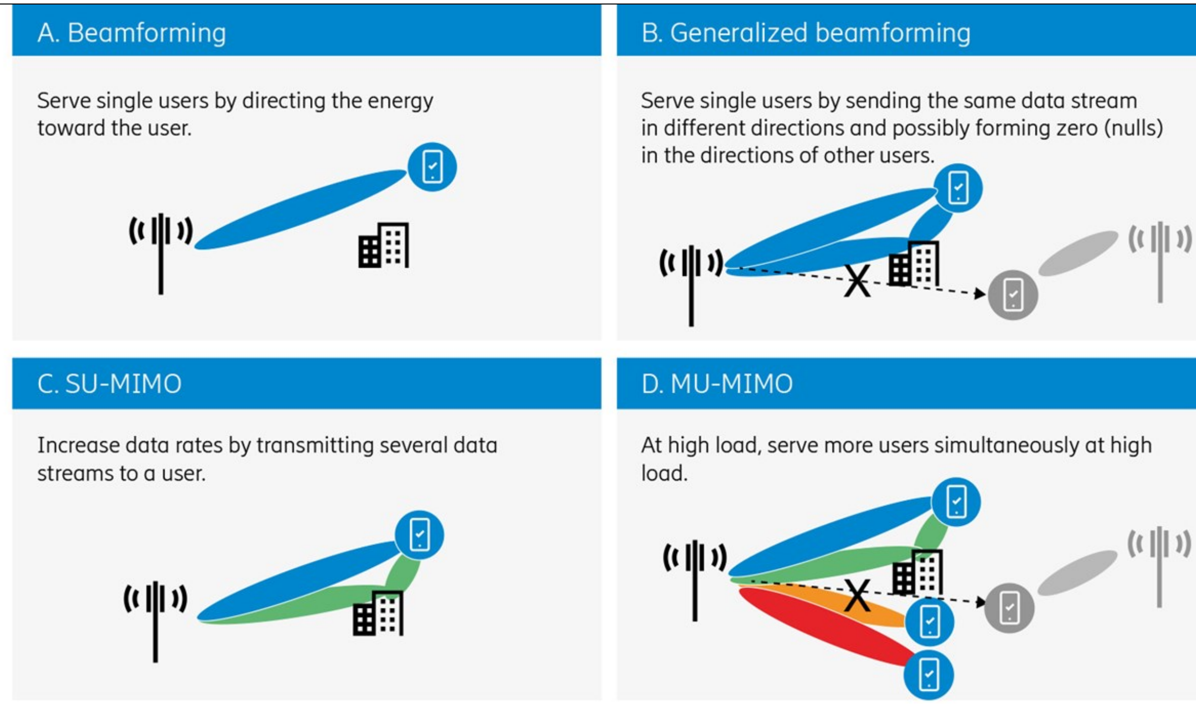


Figure 1: Beamforming and MIMO, with the different colors of the filled beams representing streams.

Although often very effective, transmitting energy in only one direction does not always provide an optimum solution. In multi-path scenarios, where the radio channel comprises multiple propagation paths from transmitter to receiver through diffraction around corners and reflections against buildings or other objects, it is beneficial to send the same data stream in several different paths (direction and/or polarization) with phases and amplitudes controlled in a way that they add constructively at the receiver [5]. This is referred to as generalized beamforming, as shown in the upper right quadrant of Figure 1. As part of generalized beamforming, it is also possible to reduce interference to other UEs, which is known as null forming. This is achieved by

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| | controlling the transmitted signals in a way that they cancel each other out at the interfered UEs.<br><br>**MIMO (Multiple Input, Multiple Output) techniques**<br>Spatial multiplexing, here referred to as MIMO, is the ability to transmit multiple data streams, using the same time and frequency resource, where each data stream can be beamformed. The purpose of MIMO is to increase throughput. MIMO builds on the basic principle that when the received signal quality is high, it is better to receive multiple streams of data with reduced power per stream, than one stream with full power. The potential is large when the received signal quality is high and the streams do not interfere with each other. The potential diminishes when the mutual interference between streams increases. MIMO works in both UL and DL, but for simplicity the description below will be based on the DL.<br><br>Single-user MIMO (SU-MIMO) is the ability to transmit one or multiple data streams, called layers, from one transmitting array to a single user. SU-MIMO can thereby increase the throughput for that user and increase the capacity of the network. The number of layers that can be supported, called the rank, depends on the radio channel. To distinguish between DL layers, a UE needs to have at least as many receiver antennas as there are layers.<br><br>SU-MIMO can be achieved by sending different layers on different polarizations in the same direction. SU-MIMO can also be achieved in a multi path environment, where there are many radio propagation paths of similar strength between the AAS and the UE, by sending different layers on different propagation paths, as shown in the bottom left quadrant of Figure 1.<br><br>In multi-user MIMO (MU-MIMO), which is shown in the bottom right quadrant of Figure 1, the AAS simultaneously sends different layers in separate beams to different users using the same time and frequency resource, thereby increasing the network capacity. In order to use MU-MIMO, the system needs to find two or more users that need to transmit or receive data at the very same time. Also, for efficient MU-MIMO, the |

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| | interference between the users should be kept low. This can be achieved by using generalized beamforming with null forming such that when a layer is sent to one user, nulls are formed in the directions of the other simultaneous users.<br><br>The achievable capacity gains from MU-MIMO depend on receiving each layer with good signal-to-interference-and-noise-ratio (SINR). As with SU-MIMO, the total DL power is shared between the different layers, and therefore the power (and thus SINR) for each user is reduced as the number of simultaneous MU-MIMO users increases. Also, as the number of users grows, the SINR will further deteriorate due to mutual interference between the users. Therefore, the network capacity typically improves as the number of MIMO layers increases, to a point at which power sharing and interference between users result in diminishing gains, and eventually also losses.<br><br>It should be noted that the practical benefits of many layers in MU-MIMO are limited by the fact that, in today's real networks, even with a high number of simultaneous connected users, there tends not to be many users who want to receive data simultaneously. This is due to the bursty (chatty) nature of data transmission to most users. Since the AAS and the transport network must be dimensioned for the maximum number of layers, the MNO needs to consider how many layers are required in their networks. In typical MBB deployments with the current 64T64R AAS variants, the vast majority of the DL and UL capacity gains can be achieved with up to 8 layers."<br><br>***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine |

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| | how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.<br><br>DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short- term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics.<br><br>The suitable channel knowledge scheme to use depends on UL coverage and UE capabilities. In cases where UL coverage is limiting, UE feedback offers a more robust |

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| | operation, whereas full UL channel estimation is applicable in scenarios with good coverage. In short, both reciprocity and UE feedback-based beamforming are needed.<br><br>**Antenna array structure**<br>The purpose of using a rectangular antenna array, as shown in section A of Figure 2, is to enable high-gain beams and make it possible to steer those beams over a range of angles. The gain is achieved, in both UL and DL, by constructively combining signals from a number of antenna elements. The more antenna elements there are, the higher the gain. Steerability is achieved by individually controlling the amplitude and phase of smaller parts of the antenna array. This is usually done by dividing the antenna array into so called sub-arrays (groups of non-overlapping elements), as shown in section C of Figure 2, and by applying two dedicated radio chains per sub-array (one per polarization) to enable control, as shown in section D. In this way it is possible to control the direction and other properties of the created antenna array beam.<br><br>Thus, as stated above by Ericsson: "What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by a suitable averaging of UL channel estimate statistics." |

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| | See, e.g., 3GPP TS 38.214 v 16.2.0 R16 (2020-07) (incorporated by reference herein)<br><br>§ 5.2.2.2 Precoding matrix indicator (PMI)<br><br>[describing Type I and Type II and Enhanced Type II Codebooks for MIMO beamforming precoding matrix]<br>…<br>5.2.2.2.1 Type I Single-Panel Codebook<br>…<br>5.2.2.2.2 Type I Multi-Panel Codebook<br>…<br>5.2.2.2.3 Type II Codebook<br>…<br>5.2.2.2.4 Type II Port Selection Codebook<br>…<br>5.2.2.2.5 Enhanced Type II Codebook<br>…<br>5.2.2.2.6 Enhanced Type II Port Selection Codebook<br>…<br><br>See, e.g., Ziao Qin and Haifan Yin, A Review of Codebooks for CSI Feedback in 5G New Radio and Beyond, arXiv:2302.09222v2 13 Jun 2023 |

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| | [describing Type I and Type II and Enhanced Type II Codebooks for MIMO beamforming precoding matrix]<br><br>Multiple-Input Multiple-Output (MIMO) has been an integral technology to improve system performance since 4G LTE R8 released in 2009. In 5G NR, this technology has evolved to massive MIMO [2] with an increasing scale of the antenna array. Massive MIMO provides higher transmission diversity, higher spatial multiplexing gain, and higher transmission directivity. Hence, higher spectral efficiency and more reliability can be achieved [3]. Particularly, the key to high transmission directivity brought by massive MIMO is beamforming, which enables multi-user spatial multiplexing. To achieve accurate beamforming, Channel State information (CSI) is the indispensable premise. At the base station (BS) side, the downlink (DL) CSI can be acquired by the feedback information from the users (UEs), i.e., CSI report [4]. Note that CSI report is more indispensable in frequency division duplex (FDD) mode than time division duplex (TDD) mode [5]. The reported CSI enables the BS to calculate the precoding matrix for beamforming and user scheduling. In 3GPP standards, the CSI report process is achieved by the configuration of the codebook and the feedback of the codewords. At first, a codebook refers to a set of pre-defined precoders, a.k.a., codewords, and the UEs feed back the indices of the codewords to the base station. With the development of the standard nowadays, the meaning of codebook extends to the whole CSI report mechanism, which helps the base station compute the precoding matrix with the feedback from the UEs.<br>The CSI report framework includes the procedure of a particular CSI reference signal (CSI-RS) transmitted by the BS and a series of feedback information from the UEs.<br>Even though 5G NR evolves from LTE, the CSI acquisition framework in NR is quite different. Particularly in LTE, the CSI acquisition framework is coupled with the transmission modes (TMs). For example, a codebook-based feedback mode is defined in TM6, also known as the close-loop scheme. At the same time, the open-loop scheme is also supported in LTE, |

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| | which means no CSI report is needed for precoding. In 5G NR, however, CSI report framework is decoupled with the TM and relies on the CSI report configurations instead. In this way, better flexibility and scalability for CSI report are achieved. More specifically, the CSI report framework configuration consists of two parts, i.e., report resources setting and report type setting [6]. The report resources setting specifies the periodic report manner and the occupied bandwidth part (BWP) according to different usages of the reference signal. For example, the CSI reference signal specializes in CSI calculation [7]. And the report type is configured based on report resources configuration. It mainly reports the CSI indicators and the corresponding codebook configuration. Particularly, the layer indicator (LI) and the rank indicator (RI) specify the optimum layer with best quality and the maximum number of transmission layers, respectively. Correspondingly, the precoding matrix indicator (PMI) is utilized for the base station to reconstruct or calculate the DL precoders.<br>The essence of CSI report framework lies in the codebook design which determines the obtained precoding matrix from CSI feedback. The corresponding PMI indicates the specific channel characteristics with a chosen codebook scheme. In fact, since 4G, the codebooks have been evolving towards characterizing more detailed channel information with less time-frequency overhead. The number of supported types of codebook has increased over time to six in 5G NR R17 to accommodate different system requirements and to maintain backward compatibility. Recently, novel methods, such as machine learning [8], joint spatial division and multiplexing (JSDM) [9] and computer vision [10], are utilized to improve the accuracy of the CSI feedback…<br>IV. TYPE II CODEBOOK<br>Type II Codebook is first proposed in 5G NR R15 as an upgrade of Type I Codebook, in order to better characterize the multi-path channel. One of the most significant improvement of Type II Codebook is the support of multiple beams. Each beam and its corresponding coefficient reflect a path with a certain angle. And up to four beams can be reported in Type II Codebook. As a result, this codebook outperforms Type I Codebook in most scenarios, nevertheless, at the cost of |

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| | increased feedback overhead.<br><br>A. PMI format<br>The PMI report for Type II Codebook turns out to be more complicated than Type I Codebook. As a tradeoff between the performance and the feedback overhead / complexity, the layer limitation υ is 2. Fig. 3 demonstrates the PMI format, which covers four kinds of beam information, i.e., the beam choice, the beam with the maximum amplitude, the beam amplitudes and the beam phases. The chosen $L \in \{2, 3, 4\}$ beams are indicated by $i_{1,1}$ and $i_{1,2}$. We should note that all layers share the same beam choice. The indicator $i_{1,1}$ contains two indices $q_1$, $q_2$, where $q_1$ and $q_2$ map the oversampling parameter in the horizontal and vertical direction, respectively. The indicator $i_{1,2}$ indicates how to choose L beams from the DFT vector set of size $N_1N_2$. The value of $i_{1,2}$ varies from 0 to<br>CLN<br>1N2<br>−1, where CLN<br>1N2 represents the number of possibilities<br>of selecting different L beams from all $N_1N_2$ beams. In<br><br>Fig. 3. The PMI format and the precoding matrix of Type II Codebook at layer l.<br>general, the gNB is equipped with dual-polarized antennas. In Type II Codebook, the same set of L beams are shared for both polarizations. As a result, 2L beam coefficients corresponding to L chosen beams are reported. These coefficients include the amplitudes and the phases. In order to reduce the complexity, only the phase information are reported in a subband manner, while the amplitudes can be reported in subband manner or wideband manner ( the reported amplitude for a certain beam is identical for all the subbands in the whole BWP), depending on configuration.<br>The wideband amplitude indicator $i_{1,4,l}$ is a vector with 2L entries, which are denoted by k(1)<br>l,i , where i ∈ {0, °§ °§ °§ 2L − 1}<br>indicates the beam index and k(1)<br>l,i ∈ {0, 1, . . . , 7}. The<br>wideband amplitude of beam i at layer l is computed by<br>p(1) l,i =□1 √2 7−k(1)l,i . The phase information reported in |

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| | every subband are indicated by $i_{2,1,l}$. Its element $c_{l,i}$ quantizes phases in a N-phase shift keying (N-PSK) manner as $e^{j2\pi c_{l,i}/N_{psk}}$, where $N_{psk} \in \{4, 8\}$. The indicator $i_{1,3,l}$ maps the index of the beam with the maximum amplitude at layer l.<br>In fact, subband amplitude report can be supported in Type II Codebook and it is indicated by a binary parameter $I_s$. Specifically, $I_s = 1$ means that subband amplitude report is enabled, while $I_s = 0$ means it does not. If $I_s = 1$, an additional indicator vector $i_{2,2,l}$ is reported to quantize the subband amplitude information with its entries being $k^{(2)}_{l,i} \in \{0, 1\}$. The reported subband amplitude is thus [ ].<br>B. PMI report compression<br>Type II Codebook supports multiple beams and subbandwise report. As a result, the feedback overhead becomes heavier compared to Type I Codebook. To balance the report accuracy and the overhead, Type II Codebook introduces a PMI report compression mechanism. The coefficients of beam with the strongest amplitude $k^{(1)}_{l,i^*_l}$ and the corresponding phase $c_{l,i^*_l}$ will not be reported, where the beam index $i^*_l$ is indicated by $i_{1,3,l}$. When Type II Codebook is configured to wideband mode, only the non-zero wideband amplitude $k^{(1)}_{l,i}$ and thecorresponding phase $c_{l,i}$ are reported to the gNB. The number of non-zero coefficients of each layer is $M^l_{nz} < 2L$. If subband mode is configured, the subband coefficients report is slightly different. The $M^l_{vr}$ stronger subband coefficients are phasequantized in a N-PSK manner, where $N_{psk} \in 4, 8$. And the remaining $M^l_{nz} - M^l_{vr}$ non-zero subband coefficients are phase-quantized with $N_{psk} = 4$. The rest $2L - M^l_{vr}$ subband coefficients are not reported, since they are very close to zero.<br>In general, the core idea of PMI report compression lies in feeding back the information of the predominant beams, and the feedback overhead is reduced by ignoring the weak beams.<br>C. Precoding matrix calculation<br>The precoding matrix calculation in Type II Codebook is |

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| | different from Type I Codebook. The main difference is that Type II Codebook supports multiple beams. Fig. 3 shows how to map the precoding matrix from the PMI in Type II Codebook.<br>In general, the precoding matrix $W_{(l)}$ is a weighted summation of multiple beams and is calculated by [ ]<br>For each beam, four types of beam information are reported, i.e., the beam choice $w_{m(i)1,m(i)}$, the wideband amplitude $p(1)_{l,i}$, the subband phase $c_{l,i}$ and the subband amplitude $p_{(2)l,i}$. In Fig. 3, the chosen L beams are denoted by B. The block matrix diag {B,B} is introduced to represent the beams for both polarizations. The matrix B is composed of L beams and each beam $w_{m(i)1,m(i)2}$ is similar to the vector $w_{m1,m2}$ in Type I Codebook. However, the indices $m(i)_1, m(i)_2$ are mapped from $i_{1,1}$ and $i_{1,2}$ as illustrated in Fig. 3. And the beam choice indices $n(i)_1$, $n(i)_2$ are calculated from $i_{1,2}$ through the algorithm in Sec. 5.2.2.2.3 of [6]. The wideband amplitude of each layer is defined by a diagonal matrix $A(l)_w$ and its element $p(1)_{l,i}$ is indicated by $i_{1,4,l}$. The wideband amplitude matrix $A(l)_w$ is always reported. The diagonal matrix $A_{(l)s}$ is the subband amplitude matrix, which is valid only if subband mode is supported. The diagonal elements of $A_{(l)s}$ are indicated by $i_{2,2,l}$. Correspondingly, the subband phase information is characterized by $P_{(l)s}$. The elements of $P(l)_s$ are mapped from $i_{2,1,l}$. The matrix $I_{N_1N_2}$ is an $N_1N_2$ °ø $N_1N_2$ identity matrix.<br>Overall, Type II Codebook shows many significant improvements, especially the support of subband amplitude and multiple beams. As a result, the CSI feedback is more accurate, which facilitates the gNB to cancel inter-user interference and allocate resources. This is also why Type II Codebook is more suitable for multi-user MIMO (MU-MIMO) than Type I Codebook. Even though Type II Codebook introduces a PMI report compression scheme to reduce the overhead, the feedback still scales with the bandwidth and the number of UEs. This problem is particularly acute in FDD mode with large number of gNB antennas. Nowadays, the increasing number of antennas and wider bandwidth call for new codebooks with high accuracy and low feedback overhead. Fortunately, a better-performing codebook called "Enhanced Type II Codebook" is proposed in 5G NR R16. |

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| | V. ENHANCED TYPE II CODEBOOK<br>The codebooks discussed before were proposed in 5G NR R15. With the evolution of 5G NR, frequency-sensitive and multi-path channel environment requires a codebook with better performance by capturing both the spatial domain and the frequency domain structures of the channel. Hence, Enhanced Type II Codebook is proposed in 5G NR R16 as an Upgrade of Type II Codebook. It is particularly suitable in a multipath scattering environment with diverse angle spread and delay spread, while the UE is capable of complex signal processing. The most significant merit of Enhanced Type II Codebook lies in feedback reduction in spatial and frequency domain. This is enabled by the channel sparsity in both spatial and frequency domains in wideband massive MIMO. Fig. 4 gives a demonstration of the feedback overhead compression. In the spatial domain, L beams are chosen to characterize the angular structure of the channel like in Type II Codebook. However, the subband amplitude is always reported in Enhanced Type II Codebook. In the frequency domain, a delay matrix $F_{(l)}$ is introduced to map the phase information of all $N_3$ subbands with $M_υ \leq N_3$ basis vectors. Hence, the subband amplitude and phase of all beams of all $N_3$ subbands are reported in $W_{(l)}$<br>$_{sb}$ with the help of $M_υ$ IDFT vectors. Due to the DFT-based compression in spatial domain and the IDFTbased compression in frequency domain, Enhanced Type II Codebook has a reduced feedback overhead compared with its predecessor.<br>According to Table 5.2.2.2.5-1 in [6], eight compression configurations, denoted by the parameter combination $(L, p_υ, β)$, for Enhanced Type II Codebook are supported. The number of basis vectors in frequency domain is calculated by $M_υ =\ p_υ N_3 R$<br>, where $p_v \in \{1/4, 1/8\}$ is the number of average basis vectors used per subband in frequency domain. $β \in \{1/4, 1/2, 3/4\}$ is the feedback overhead compression ratio from the full dimension to the reduced dimension. The parameter R is either one or two, depending on the higher-layer configurations. Therefore, in spatial domain and frequency domain, a total of $LM_υ$ basis vectors are utilized |

to characterize the precoding matrix.

Fig. 4. The compression in spatial and frequency domain and the PMI format of Enhanced Type II Codebook.

A. PMI format

The PMI format in Enhanced Type II Codebook is more complicated than Type II Codebook. As illustrated in Figure 4, the PMI format includes the beam indicators $i_{1,1}$, $i_{1,2}$, the delay indicators $i_{1,5}$, $i_{1,6,l}$, the bitmap indicator $i_{1,7,l}$, the strongest beam indicator $i_{1,8,l}$, the wideband amplitude indicator $i_{2,3,l}$, the feedback amplitude indicator $i_{2,4,l}$ and the feedback phase indicator $i_{2,5,l}$.

On one hand, the beam indicators are similar to the ones in Type II Codebook. The beam selection is mapped by $i_{1,1}$, $i_{1,2}$ like Type II Codebook. The wideband amplitude indicator $i_{2,3,l}$ consists of two coefficients, $k^{(1)}_{l,0}$ and $k^{(1)}_{l,1}$.

They quantize the wideband amplitude in each polarization direction with 4 bits according to the mapping relationship in Table 5.2.2.2.5-2 of [6]. The quantified wideband amplitude at each polarization direction is denoted by $p^{(1)}_{l,0}$ and $p^{(1)}_{l,1}$.

Compared with the wideband amplitude indicator $i_{1,4,l}$ in Type II Codebook, the amplitude quantization in Enhanced Type II Codebook increases from 3 bits to 4 bits. Moreover, the subband beam information is always available in Enhanced Type II Codebook. It is reported in angle-delay domain. The coefficients $k^{(2)}_{l,i,f}$ of $i_{2,4,l}$ quantize the feedback amplitude $p^{(2)}_{l,i,f}$ with 3 bits, outperforming the 1-bit quantization of the subband amplitude in Type II Codebook. Corresponding to the feedback amplitude $p^{(2)}_{l,i,f}$, the coefficients $\phi_{l,i,f}$ of indicator $i_{2,5,l}$ quantize the feedback phase $c_{l,i,f}$ in a 4PSK manner.

The indicator $i_{1,8,l}$ records the index of the strongest subband coefficient at layer l, similar to the indicator $i_{1,3,l}$ in Type II Codebook.

On the other hand, due to the compression in frequency

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| | domain and the report of delay information, several new indicators $i_{1,5}$, $i_{1,6,l}$, $i_{1,7,l}$ are introduced. The subband amplitude and phase information is reported in $M_υ$ dimension instead of $N_3$, due to the frequency domain compression. The frequency basis vectors are determined by a vector $n_{3,l} \in C^{1°øM_υ}$. Each element of this vector, denoted by $n^{(f)}_{3,l} \in \{0, 1 °§ °§ °§N_3 - 1\}$ , $f \in \{0, °§ °§ °§M_υ - 1\}$, indicates the delay information of the corresponding frequency basis vector through the relationship $\tau^{(f)}_{n_f,l} = e^{j2\pi n m^{(f)}_{3,l}}$ . $N_3$ is the subband index. The vector $n_{3,l}$ is computed based on the indicators $i_{1,5}$, $i_{1,6,l}$ that are fed back by the UE, according to the algorithm in Sec. 5.2.2.2.5 of [6]. Denote the index of the strongest frequency basis vector at the layer l by $f^*_l$. The frequency basis vector $n_{3,l}$ is reorganized with respect to $f^*_l$ such that $n^{(f)}_{3,l} = n^{(f)}_{3,l} - n^{(f^*_l)}_{3,l}$ mod $N_3$. Thus, $n^{(f^*_l)}_{3,l} = 0$ after remapping. Likewise, the frequency basis vector index f is reorganized with respect to $f^*_l$ such that $f = (f - f^*_l)$ mod$M_υ$, and therefore, $f^*_l = 0$.<br><br>B. PMI report compression<br>Although the problem of feedback overhead is alleviated by IDFT based frequency domain compression in Enhanced Type II Codebook, the PMI report still consumes valuable timefrequency resources. In order to further reduce the overhead, some PMI compression mechanisms are introduced. First, the indices of the strongest beam at the layer l are denoted by $i^*_l$. The coefficients of $i_{2,4,l}$, $i_{2,5,l}$ corresponding to $i^*_l$, $f^*_l$, as well as the wideband amplitude $i_{2,3,l}$ with indices equal to $\lfloor i^*_l /L\rfloor$ are not reported. Then, similar to Type II Codebook, only non-zero coefficients of $i_{2,4,l}$ and $i_{2,5,l}$ are reported. The indicator $i_{1,7,l}$ serves as a bitmap with size $1 °ø 2LM_υ$ in order to show whether the UE reports the corresponding coefficients in $W^{(l)}$ |

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| | $_{sb}$ or not. Since some values in $W^{(l)}_{sb}$ are negligible, this bitmap will help reduce the feedback overhead. The number of reported coefficients of all layers is denoted by $M_{nz} = \sum_{l=1}^{\upsilon} M^{l}_{nz}$. The number of non-zeros coefficients $M^{l}_{nz}$ is equal to the summation of the coefficients of the bitmap indicator $i_{1,7,l}$ at layer l. As a result, $2L\upsilon M_v - M_{nz}$ coefficients of $i_{2,4,l}$, $i_{2,5,l}$ are not reported, where υ is the number of layers. Since in each layer, only relative values with respect to the coefficient with the maximum amplitude are needed for feedback, the number of all reported coefficients $k^{(2)}_{l,i,f}$, $c_{l,i,f}$ is thus $M_{nz} - \upsilon$.<br>C. Precoding matrix calculation<br>In general, the precoding matrix calculation in Enhanced Type II Codebook has a lot in common with Type II Codebook. The precoding matrix $W^{(n_f,l)}$ is similar to $W^{(l)}$ in Fig. 3 The main difference lies in the frequency domain compression and the mapping of the delay information. Fig. 4 demonstrates the relationship between the PMI and the precoding matrix $W^{(n_f,l)}$. The beam selecting matrix B is consistent with Type II Codebook. However, the wideband amplitude matrix $A^{(l)}_{w}$ is different, as it is composed of a block diagonal matrix with the two blocks reflecting the wideband amplitudes for both polarization instead of reusing the same set of wideband amplitudes among the two polarizations as in Type II Codebook. The reconstruction of the subband phase and amplitude is also quite different from Type II Codebook, because of the frequency domain compression with IDFT basis vectors. The amplitude and phase information of all subbands are transformed to angle-delay domain, quantized, and fed back to the gNB. Then the gNB reconstructs the information by reverse transformation with the quantized coefficients. Generally speaking, Enhanced Type II Codebook is more sophisticated than Type II Codebook. Despite the complexity, |

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| | Enhanced Type II Codebook shows great potential in improving system spectral efficiency. The detailed PMI report in Enhanced Type II Codebook characterizes much more channel structure information, especially in the delay domain. The key lies in the exploitation of the multipath angle-delay structure of wideband massive MIMO by means of DFT and IDFT transformations. Thanks to the feedback overhead reduction in frequency domain, the maximum number of layers in Enhanced Type II Codebook increases to four. And the maximum number of beams L increases from four to six compared to Type II Codebook. In fact, higher frequency band and larger antenna arrays are given great expectations for 5G NR and beyond. In such case, the angle and delay structure of the channel is more obvious and should be captured by the codebooks in order to facilitate the CSI feedback. No doubt that Enhanced Type II Codebook is a good choice in this circumstance. However, the feedback overhead of Enhanced Type II Codebook is still a serious problem, especially when the number of antennas and the bandwidth are large. Achieving more accurate CSI feedback with less overhead is an everlasting effort of industry. |

- layers: The streams in MIMO-enabled spatial multiplexing, i.e., transmitting signals simultaneously in the same time/frequency resources.
- subband: Several consecutive resource blocks (RBs). The bandwidth of a subband may be configured as 4, 8, 16 RBs, etc.
- beam: It means a certain spatial direction, normally corresponding to a column vector from a one-dimensional or two-dimensional DFT matrix, when the antenna array topology is an uniform linear array (ULA) or an uniform planar array (UPA), respectively.
- antenna port: This terminology is not related to a physical "port" anymore. The symbols transmitted on the same antenna port can be assumed to share the same effective channel.
- $v$: The layer limitation configured by the gNB and indicated by RI.
- $N_{\mathrm{AP}}$: The number of antenna ports at the gNB.
- $N_1, N_2, O_1, O_2$: $N_1$ and $N_2$ denote the number of antennas elements in the horizontal and vertical direction, respectively. $O_1$ and $O_2$ are the oversampling factors in the horizontal and vertical direction, respectively.
- $N_g$: The number of antenna panels.
- $L$: The number of reported beams in a certain codebook.
- $N_3$: The number of subbands in a BWP.

The major characteristic of each codebook lies in how it maps the precoding matrix from the reported PMI. Overall, the precoding matrix consists of beam information and phase information, which rely on the reported beam indicators and phase indicators. To be more specific, the UE utilizes the received signal to search for the optimal codeword based on the precoder form constraint. Then it reports the codeword index as the beam indicator and quantizes the corresponding phase as the phase indicator. In the following sections, we focus on introducing the PMI format and the calculation of the precoding matrix.

## III. Type I Codebook

In R17, two sub-types of Type I Codebook are supported, i.e., Type I Codebook with Single-Panel and Type I Codebook with Multi-Panel. The main difference between the two codebooks is the number of the supported transmit antenna panels. First, we discuss Type I Codebook with Single-Panel.

### *A. Type I Codebook with Single-Panel*

Type I Codebook with Single-Panel is relatively straightforward as the reported PMI reflects the information of a single beam, including the beam selection and the co-phasing information among the dual-polarized antennas. Under the assumption of an uniform planar array (UPA) at the gNB as in [19], the chosen beam is selected from the set of 2D DFT vectors with spatial oversampling, indicated by $(N_1, N_2, O_1, O_2)$. These parameters are specified by Table 5.2.2.2.1-2 in [6]. Fig. 2 demonstrates the physical meanings of the PMI. Define the PMI vector as $\mathbf{I} = \begin{bmatrix} \mathbf{I}_1 & \mathbf{I}_2 \end{bmatrix}$, where $\mathbf{I}_1$ reports the chosen beam information and $\mathbf{I}_2$ indicates the corresponding phase information, respectively. $\mathbf{I}_1$ includes two indicators $i_{1,1}$ and $i_{1,2}$. The indicator $i_{1,1}$ maps the horizontal beam index $m_1$ and the indicator $i_{1,2}$ maps the vertical beam index $m_2$. The second part of the PMI $\mathbf{I}_2 = i_2$ maps the co-phasing information by $\varphi_n = e^{j\pi n/2}$. We should note that $n$ is binary, except when $v = 1$, $n \in \{0, 1, 2, 3\}$. When the layer limitation $v \leq 2$, the beam choice is indicated together by $i_{1,1}, i_{1,2}, i_2$, otherwise by $i_{1,1}, i_{1,2}$.

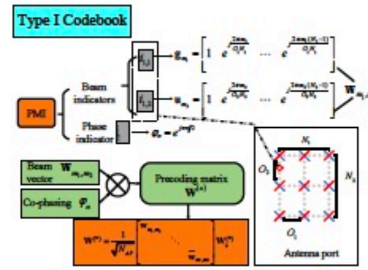


Fig. 2. The 2D antenna port structure, PMI format and precoding matrix calculation of Type I Codebook.

The 2D antenna array structure and the PMI format of Type I Codebook are illustrated in Fig. 2. The 2D beam $\mathbf{w}_{m_1,m_2}$ is a Kronecker product of the vertical beam $\mathbf{u}_{m_2}$ and the horizontal beam $\mathbf{g}_{m_1}$. And the neighboring 2D beam $\bar{\mathbf{w}}_{m_1,m_2}$ consists of a different horizontal beam $\bar{\mathbf{g}}_{m_1}$ and the same vertical beam with $\mathbf{w}_{m_1,m_2}$. The indices $m_1$ and $m_2$ are indicated by $i_{1,1}$ and $i_{1,2}$, respectively. Fig. 2 also demonstrates how to calculate the precoding matrix from the reported PMI and the equation is given

$$\mathbf{W}^{(v)} = \frac{1}{\sqrt{N_{\mathrm{AP}}}} \begin{bmatrix} \mathbf{w}_{m_1,m_2} & & \\ & \ddots & \\ & & \bar{\mathbf{w}}_{m_1,m_2} \end{bmatrix} \mathbf{W}_2^{(v)}$$

The precoding matrix $\mathbf{W}^{(v)}$ is made of the beam vector and phasing information, which are indicated by the 2D beam $\mathbf{w}_{m_1,m_2}$ and the subband phase $\phi_n$, respectively. This procedure is relatively straightforward and only includes one beam and the co-phasing information. More specifically, the 2D beam $\mathbf{w}_{m_1,m_2}$ is frequency-irrelevant and reported in wideband mode. In contrast, the co-phasing matrix $\mathbf{W}_2^{(v)}$ is frequency-dependent and needs to be reported per subband. The column vector of $\mathbf{W}_2^{(v)}$ characterizes the co-phasing information of each layer, which is specified in Table 5.2.2.2.1-(5-12) in [6]. However, when $N_{\mathrm{AP}} > 16$ and $v \in \{3, 4\}$, the matrix $\mathbf{W}_2^{(v)}$ also indicates a beam choice between the beam $\mathbf{w}_{m_1,m_2}$ and another beam $\bar{\mathbf{w}}_{m_1,m_2}$ which is defined in Table 5.2.2.2.1 of [6].

Evolved from LTE, this codebook is rather simple and works well in strong line of sight (LoS) scenarios. The number of reported coefficients is smaller compared to other codebooks. The computational complexity of calculating the precoding matrix from the PMI is the lowest. Due to the concise structure

of Type I Codebook with Single-Panel, the layer limitation can be eight. However, the performance of this codebook is limited, particularly so in multipath scenarios, since only one beam is used for signal transmission.

### B. Type I Codebook with Multi-Panel

This codebook may be applied when the antenna array at the gNB consists of multiple antenna panels instead of one. In order to facilitate the implementation, the number of antenna ports $N_{\mathrm{AP}}$ is limited to the set $\{8, 16, 32\}$ and the layer limitation descends to $\upsilon \leq 4$. In this codebook, additional co-phasing information needs to be reported.

Compared to Type I Codebook with Single-Panel, a new indicator vector $\mathbf{i}_{1,4}$ is introduced in Type I Codebook with Multi-Panel. The dimension of the vector $\mathbf{i}_{1,4}$ is associated with the number of antenna panels $N_g$ and the codebook mode $C_m$, varying from one to three. It indicates the inter-panel co-phasing information and the dual-polarization co-phasing information. Other indices in $\mathbf{I}_1$ are consistent with Type I Codebook with Single-Panel. However, the indicator $\mathbf{I}_2$ is reported in a different manner. When $C_m = 2$, it consists of three indices, $i_{2,0}$, $i_{2,1}$ and $i_{2,1}$. Otherwise, it only includes one index $i_2$, as in Type I Codebook with Single-Panel.

The precoding matrix $\mathbf{W}^{(\upsilon)}$ of Type I Codebook with Multi-Panel is similar to Type I Codebook with Single-Panel. The main difference lies in the co-phasing matrix $\mathbf{W}_2^{(\upsilon)}$, which is jointly indicated by $\mathbf{I}_2$ and $\mathbf{i}_{1,4}$. It relies on the parameter combination $(N_g, C_m, \upsilon)$, which is specified in Table 5.2.2.2.2-1 of [6]. Particularly, the additional co-phasing information is quantified by $a_p = e^{j\pi/4}e^{j\pi p/2}$ and $b_n = e^{-j\pi/4}e^{j\pi n/2}$. The indices $n \in n_0, n_1, n_2$ are indicated by $\mathbf{I}_2$ and $p \in p_1, p_2$ are indicated by $\mathbf{i}_{1,4}$.

In general, the two sub-types of Type I Codebook mentioned above are both able to provide the beam information and the co-phasing information. It is particularly applicable in a single-user MIMO (SU-MIMO) scenario. Besides, Type I Codebook lays the foundation of the other codebooks in subsequent releases of 5G NR. However, the drawbacks of Type I Codebook are also explicit. Due to the large bandwidth in 5G NR, the channels of subbands differ a lot. Type I Codebook only allows for one spatial beam, which will be used in the whole BWP. Hence, it has limited capability to characterize the channel with multipath. As a result, the spectral efficiency performance of Type I Codebook is unsatisfactory, especially in massive MIMO. Therefore, other types of codebooks are naturally proposed as enhancements, such as Type II Codebook.

## IV. Type II Codebook

Type II Codebook is first proposed in 5G NR R15 as an upgrade of Type I Codebook, in order to better characterize the multi-path channel. One of the most significant improvement of Type II Codebook is the support of multiple beams. Each beam and its corresponding coefficient reflect a path with a certain angle. And up to four beams can be reported in Type II Codebook. As a result, this codebook outperforms Type I Codebook in most scenarios, nevertheless, at the cost of increased feedback overhead.

### A. PMI format

The PMI report for Type II Codebook turns out to be more complicated than Type I Codebook. As a tradeoff between the performance and the feedback overhead / complexity, the layer limitation $\upsilon$ is 2. Fig. 3 demonstrates the PMI format, which covers four kinds of beam information, i.e., the beam choice, the beam with the maximum amplitude, the beam amplitudes and the beam phases. The chosen $L \in \{2, 3, 4\}$ beams are indicated by $\mathbf{i}_{1,1}$ and $i_{1,2}$. We should note that all layers share the same beam choice. The indicator $\mathbf{i}_{1,1}$ contains two indices $q_1, q_2$, where $q_1$ and $q_2$ map the oversampling parameter in the horizontal and vertical direction, respectively. The indicator $i_{1,2}$ indicates how to choose $L$ beams from the DFT vector set of size $N_1N_2$. The value of $i_{1,2}$ varies from 0 to $C^L_{N_1N_2} - 1$, where $C^L_{N_1N_2}$ represents the number of possibilities of selecting different $L$ beams from all $N_1N_2$ beams. In

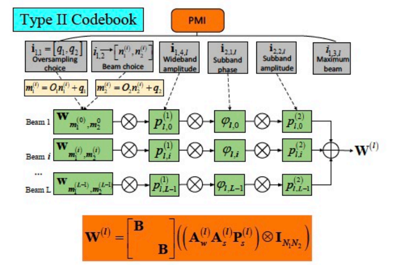


Fig. 3. The PMI format and the precoding matrix of Type II Codebook at layer $l$.

general, the gNB is equipped with dual-polarized antennas. In Type II Codebook, the same set of $L$ beams are shared for both polarizations. As a result, $2L$ beam coefficients corresponding to $L$ chosen beams are reported. These coefficients include the amplitudes and the phases. In order to reduce the complexity, only the phase information are reported in a subband manner, while the amplitudes can be reported in subband manner or wideband manner ( the reported amplitude for a certain beam is identical for all the subbands in the whole BWP), depending on configuration.

The wideband amplitude indicator $\mathbf{i}_{1,4,l}$ is a vector with $2L$ entries, which are denoted by $k_{l,i}^{(1)}$, where $i \in \{0, \cdots 2L - 1\}$ indicates the beam index and $k_{l,i}^{(1)} \in \{0, 1, \ldots, 7\}$. The wideband amplitude of beam $i$ at layer $l$ is computed by $p_{l,i}^{(1)} = (1/\sqrt{2})^{7-k_{l,i}^{(1)}}$. The phase information reported in every subband are indicated by $\mathbf{i}_{2,1,l}$. Its element $c_{l,i}$ quantizes phases in a N-phase shift keying (N-PSK) manner as $e^{j2\pi c_{l,i}/N_{\mathrm{psk}}}$, where $N_{\mathrm{psk}} \in \{4, 8\}$. The indicator $i_{1,3,l}$ maps the index of the beam with the maximum amplitude at layer $l$.

In fact, subband amplitude report can be supported in Type II Codebook and it is indicated by a binary parameter $I_s$. Specifically, $I_s = 1$ means that subband amplitude report is

enabled, while $I_s = 0$ means it does not. If $I_s = 1$, an additional indicator vector $\mathrm{i}_{2,2,l}$ is reported to quantize the subband amplitude information with its entries being $k_{l,i}^{(2)} \in \{0, 1\}$. The reported subband amplitude is thus $p_{l,i}^{(2)} = (1/\sqrt{2})^{1-k_{l,i}^{(2)}}$.

### B. PMI report compression

Type II Codebook supports multiple beams and subband-wise report. As a result, the feedback overhead becomes heavier compared to Type I Codebook. To balance the report accuracy and the overhead, Type II Codebook introduces a PMI report compression mechanism. The coefficients of beam with the strongest amplitude $k_{l,i_l^*}^{(1)}$ and the corresponding phase $c_{l,i_l^*}$ will not be reported, where the beam index $i_l^*$ is indicated by $i_{1,3,l}$. When Type II Codebook is configured to wideband mode, only the non-zero wideband amplitude $k_{l,i}^{(1)}$ and the corresponding phase $c_{l,i}$ are reported to the gNB. The number of non-zero coefficients of each layer is $M_{\mathrm{nz}}^{l} < 2L$. If subband mode is configured, the subband coefficients report is slightly different. The $M_{\mathrm{vr}}^{l}$ stronger subband coefficients are phase-quantized in a N-PSK manner, where $N_{\mathrm{psk}} \in 4, 8$. And the remaining $M_{\mathrm{nz}}^{l} - M_{\mathrm{vr}}^{l}$ non-zero subband coefficients are phase-quantized with $N_{\mathrm{psk}} = 4$. The rest $2L - M_{\mathrm{vr}}^{l}$ subband coefficients are not reported, since they are very close to zero. In general, the core idea of PMI report compression lies in feeding back the information of the predominant beams, and the feedback overhead is reduced by ignoring the weak beams.

### C. Precoding matrix calculation

The precoding matrix calculation in Type II Codebook is different from Type I Codebook. The main difference is that Type II Codebook supports multiple beams. Fig. 3 shows how to map the precoding matrix from the PMI in Type II Codebook.

In general, the precoding matrix $\mathbf{W}^{(l)}$ is a weighted summation of multiple beams and is calculated by

$$\mathbf{W}^{(l)} = \begin{bmatrix} \mathbf{B} & \\ & \mathbf{B} \end{bmatrix} \left( \left( \mathbf{A}_w^{(l)} \mathbf{A}_s^{(l)} \mathbf{P}_s^{(l)} \right) \otimes \mathbf{I}_{N_1 N_2} \right)$$

For each beam, four types of beam information are reported, i.e., the beam choice $\mathrm{w}_{m_1^{(i)}, m_2^{(i)}}$, the wideband amplitude $p_{l,i}^{(1)}$, the subband phase $c_{l,i}$ and the subband amplitude $p_{l,i}^{(2)}$. In Fig. 3, the chosen $L$ beams are denoted by $\mathrm{B}$. The block matrix $\mathrm{diag}\{\mathrm{B}, \mathrm{B}\}$ is introduced to represent the beams for both polarizations. The matrix $\mathrm{B}$ is composed of $L$ beams and each beam $\mathrm{w}_{m_1^{(i)}, m_2^{(i)}}$ is similar to the vector $\mathrm{w}_{m_1, m_2}$ in Type I Codebook. However, the indices $m_1^{(i)}, m_2^{(i)}$ are mapped from $\mathrm{i}_{1,1}$ and $i_{1,2}$ as illustrated in Fig. 3. And the beam choice indices $n_1^{(i)}$, $n_2^{(i)}$ are calculated from $i_{1,2}$ through the algorithm in Sec. 5.2.2.2.3 of [6]. The wideband amplitude of each layer is defined by a diagonal matrix $\mathbf{A}_w^{(l)}$ and its element $p_{l,i}^{(1)}$ is indicated by $\mathrm{i}_{1,4,l}$. The wideband amplitude matrix $\mathbf{A}_w^{(l)}$ is always reported. The diagonal matrix $\mathbf{A}_s^{(l)}$ is the subband amplitude matrix, which is valid only if subband mode is supported. The diagonal elements of $\mathbf{A}_s^{(l)}$ are indicated by $\mathrm{i}_{2,2,l}$. Correspondingly, the subband phase information is characterized by $\mathbf{P}_s^{(l)}$. The elements of $\mathbf{P}_s^{(l)}$ are mapped from $\mathrm{i}_{2,1,l}$. The matrix $I_{N_1 N_2}$ is an $N_1 N_2 \times N_1 N_2$ identity matrix.

Overall, Type II Codebook shows many significant improvements, especially the support of subband amplitude and multiple beams. As a result, the CSI feedback is more accurate, which facilitates the gNB to cancel inter-user interference and allocate resources. This is also why Type II Codebook is more suitable for multi-user MIMO (MU-MIMO) than Type I Codebook. Even though Type II Codebook introduces a PMI report compression scheme to reduce the overhead, the feedback still scales with the bandwidth and the number of UEs. This problem is particularly acute in FDD mode with large number of gNB antennas. Nowadays, the increasing number of antennas and wider bandwidth call for new codebooks with high accuracy and low feedback overhead. Fortunately, a better-performing codebook called "Enhanced Type II Codebook" is proposed in 5G NR R16.

## V. Enhanced Type II Codebook

The codebooks discussed before were proposed in 5G NR R15. With the evolution of 5G NR, frequency-sensitive and multi-path channel environment requires a codebook with better performance by capturing both the spatial domain and the frequency domain structures of the channel. Hence, Enhanced Type II Codebook is proposed in 5G NR R16 as an Upgrade of Type II Codebook. It is particularly suitable in a multipath scattering environment with diverse angle spread and delay spread, while the UE is capable of complex signal processing.

The most significant merit of Enhanced Type II Codebook lies in feedback reduction in spatial and frequency domain. This is enabled by the channel sparsity in both spatial and frequency domains in wideband massive MIMO. Fig. 4 gives a demonstration of the feedback overhead compression. In the spatial domain, $L$ beams are chosen to characterize the angular structure of the channel like in Type II Codebook. However, the subband amplitude is always reported in Enhanced Type II Codebook. In the frequency domain, a delay matrix $\mathbf{F}^{(l)}$ is introduced to map the phase information of all $N_3$ subbands with $M_v \le N_3$ basis vectors. Hence, the subband amplitude and phase of all beams of all $N_3$ subbands are reported in $\mathbf{W}_{\mathrm{sb}}^{(l)}$ with the help of $M_v$ IDFT vectors. Due to the DFT-based compression in spatial domain and the IDFT-based compression in frequency domain, Enhanced Type II Codebook has a reduced feedback overhead compared with its predecessor.

According to Table 5.2.2.2.5-1 in [6], eight compression configurations, denoted by the parameter combination $(L, p_v, \beta)$, for Enhanced Type II Codebook are supported. The number of basis vectors in frequency domain is calculated by $M_v = \lceil p_v \frac{N_3}{R} \rceil$, where $p_v \in \{1/4, 1/8\}$ is the number of average basis vectors used per subband in frequency domain. $\beta \in \{1/4, 1/2, 3/4\}$ is the feedback overhead compression ratio from the full dimension to the reduced dimension. The parameter $R$ is either one or two, depending on the higher-layer configurations. Therefore, in spatial domain and frequency domain, a total of $LM_v$ basis vectors are utilized to characterize the precoding matrix.

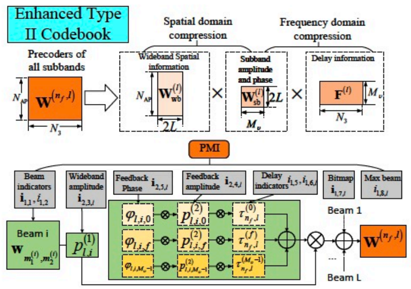


Fig. 4. The compression in spatial and frequency domain and the PMI format of Enhanced Type II Codebook.

### A. PMI format

The PMI format in Enhanced Type II Codebook is more complicated than Type II Codebook. As illustrated in Figure 4, the PMI format includes the beam indicators $\mathbf{i}_{1,1}, i_{1,2}$, the delay indicators $i_{1,5}, i_{1,6,l}$, the bitmap indicator $i_{1,7,l}$, the strongest beam indicator $i_{1,8,l}$, the wideband amplitude indicator $\mathbf{i}_{2,3,l}$, the feedback amplitude indicator $\mathbf{i}_{2,4,l}$ and the feedback phase indicator $\mathbf{i}_{2,5,l}$.

On one hand, the beam indicators are similar to the ones in Type II Codebook. The beam selection is mapped by $\mathbf{i}_{1,1}, i_{1,2}$ like Type II Codebook. The wideband amplitude indicator $\mathbf{i}_{2,3,l}$ consists of two coefficients, $k_{l,0}^{(1)}$ and $k_{l,1}^{(1)}$. They quantize the wideband amplitude in each polarization direction with 4 bits according to the mapping relationship in Table 5.2.2.2.5-2 of [6]. The quantified wideband amplitude at each polarization direction is denoted by $p_{l,0}^{(1)}$ and $p_{l,1}^{(1)}$. Compared with the wideband amplitude indicator $\mathbf{i}_{1,4,l}$ in Type II Codebook, the amplitude quantization in Enhanced Type II Codebook increases from 3 bits to 4 bits. Moreover, the subband beam information is always available in Enhanced Type II Codebook. It is reported in angle-delay domain. The coefficients $k_{l,i,f}^{(2)}$ of $\mathbf{i}_{2,4,l}$ quantize the feedback amplitude $p_{l,i,f}^{(2)}$ with 3 bits, outperforming the 1-bit quantization of the subband amplitude in Type II Codebook. Corresponding to the feedback amplitude $p_{l,i,f}^{(2)}$, the coefficients $\phi_{l,i,f}$ of indicator $\mathbf{i}_{2,5,l}$ quantize the feedback phase $c_{l,i,f}$ in a 4PSK manner. The indicator $i_{1,8,l}$ records the index of the strongest subband coefficient at layer $l$, similar to the indicator $i_{1,3,l}$ in Type II Codebook.

On the other hand, due to the compression in frequency domain and the report of delay information, several new indicators $i_{1,5}, i_{1,6,l}, \mathbf{i}_{1,7,l}$ are introduced. The subband amplitude and phase information is reported in $M_\upsilon$ dimension instead of $N_3$, due to the frequency domain compression. The frequency basis vectors are determined by a vector $\mathbf{n}_{3,l} \in \mathbb{C}^{1\times M_\upsilon}$. Each element of this vector, denoted by $n_{3,l}^{(f)} \in \{0, 1 \cdots N_3 - 1\}, f \in \{0, \cdots M_\upsilon - 1\}$, indicates the delay information of the corresponding frequency basis vector through the relationship $\tau_{n_f,l}^{(f)} = e^{j2\pi n_f n_{3,l}^{(f)}/N_3}$ is the subband index. The vector $\mathbf{n}_{3,l}$ is computed based on the indicators $i_{1,5}, i_{1,6,l}$ that are fed back by the UE, according to the algorithm in Sec. 5.2.2.2.5 of [6]. Denote the index of the strongest frequency basis vector at the layer $l$ by $f_l^*$. The frequency basis vector $\mathbf{n}_{3,l}$ is reorganized with respect to $f_l^*$ such that $n_{3,l}^{(f)} = \left(n_{3,l}^{(f)} - n_{3,l}^{(f_l^*)}\right) \bmod N_3$. Thus, $n_{3,l}^{(f_l^*)} = 0$ after remapping. Likewise, the frequency basis vector index $f$ is reorganized with respect to $f_l^*$ such that $f = (f - f_l^*) \bmod M_\upsilon$, and therefore, $f_l^* = 0$.

### B. PMI report compression

Although the problem of feedback overhead is alleviated by IDFT based frequency domain compression in Enhanced Type II Codebook, the PMI report still consumes valuable time-frequency resources. In order to further reduce the overhead, some PMI compression mechanisms are introduced.

First, the indices of the strongest beam at the layer $l$ are denoted by $i_l^*$. The coefficients of $\mathbf{i}_{2,4,l}, \mathbf{i}_{2,5,l}$ corresponding to $i_l^*, f_l^*$, as well as the wideband amplitude $\mathbf{i}_{2,3,l}$ with indices equal to $\lfloor i_l^*/L \rfloor$ are not reported. Then, similar to Type II Codebook, only non-zero coefficients of $\mathbf{i}_{2,4,l}$ and $\mathbf{i}_{2,5,l}$ are reported. The indicator $\mathbf{i}_{1,7,l}$ serves as a bitmap with size $1 \times 2LM_\upsilon$ in order to show whether the UE reports the corresponding coefficients in $\mathbf{W}_{\text{sb}}^{(l)}$ or not. Since some values in $\mathbf{W}_{\text{sb}}^{(l)}$ are negligible, this bitmap will help reduce the feedback overhead. The number of reported coefficients of all layers is denoted by $M_{\text{nz}} = \sum_{l=1}^{\upsilon} M_{\text{nz}}^l$. The number of non-zeros coefficients $M_{\text{nz}}^l$ is equal to the summation of the coefficients of the bitmap indicator $\mathbf{i}_{1,7,l}$ at layer $l$. As a result, $2L\upsilon M_\upsilon - M_{\text{nz}}$ coefficients of $\mathbf{i}_{2,4,l}, \mathbf{i}_{2,5,l}$ are not reported, where $\upsilon$ is the number of layers. Since in each layer, only relative values with respect to the coefficient with the maximum amplitude are needed for feedback, the number of all reported coefficients $k_{l,i,f}^{(2)}, c_{l,i,f}$ is thus $M_{\text{nz}} - \upsilon$.

### C. Precoding matrix calculation

In general, the precoding matrix calculation in Enhanced Type II Codebook has a lot in common with Type II Codebook. The precoding matrix $\mathbf{W}^{(n_f,l)}$ is similar to $\mathbf{W}^{(l)}$ in Fig. 3 The main difference lies in the frequency domain compression and the mapping of the delay information. Fig. 4 demonstrates the relationship between the PMI and the precoding matrix $\mathbf{W}^{(n_f,l)}$. The beam selecting matrix $\mathbf{B}$ is consistent with Type II Codebook. However, the wideband amplitude matrix $\mathbf{A}_w^{(l)}$ is different, as it is composed of a block diagonal matrix with the two blocks reflecting the wideband amplitudes for both polarization instead of reusing the same set of wideband amplitudes among the two polarizations as in Type II Codebook. The reconstruction of the subband phase and amplitude is also quite different from Type II Codebook, because of the frequency domain compression with IDFT basis vectors. The amplitude and phase information of all subbands are transformed to angle-delay domain, quantized, and fed back to the gNB. Then the gNB reconstructs the information by reverse transformation with the quantized coefficients.

Generally speaking, Enhanced Type II Codebook is more sophisticated than Type II Codebook. Despite the complexity, Enhanced Type II Codebook shows great potential in improving system spectral efficiency. The detailed PMI report in Enhanced Type II Codebook characterizes much more channel structure information, especially in the delay domain. The key lies in the exploitation of the multipath angle-delay structure of wideband massive MIMO by means of DFT and IDFT transformations. Thanks to the feedback overhead reduction in frequency domain, the maximum number of layers in Enhanced Type II Codebook increases to four. And the maximum number of beams $L$ increases from four to six compared to Type II Codebook. In fact, higher frequency band and larger antenna arrays are given great expectations for 5G NR and beyond. In such case, the angle and delay structure of the channel is more obvious and should be captured by the codebooks in order to facilitate the CSI feedback. No doubt that Enhanced Type II Codebook is a good choice in this circumstance. However, the feedback overhead of Enhanced Type II Codebook is still a serious problem, especially when the number of antennas and the bandwidth are large. Achieving more accurate CSI feedback with less overhead is an everlasting effort of industry.

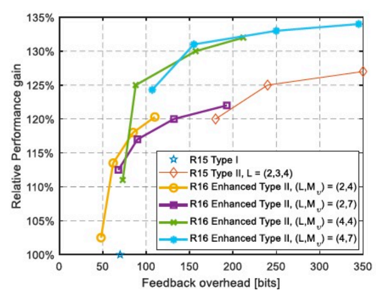


Fig. 5. The performance of Enhanced Type II Codebook vs. feedback overhead, MU-MIMO, 32 ports, rank = 1, resource utilization (RU) $\approx 70\%$, $\beta = \{\frac{1}{8}, \frac{1}{4}, \frac{1}{2}, \frac{3}{4}\}$.

According to the technical report [20], the relative gains of throughput for Enhanced Type II Codebook is demonstrated in Fig. 5. And four different feedback overhead compress ratios $\beta = \{\frac{1}{8}, \frac{1}{4}, \frac{1}{2}, \frac{3}{4}\}$ are evaluated. The parameter $(L, M_v)$ stands for the number of the spatial-frequency basis vectors. Learned from Fig. 5, Enhanced Type II Codebook achieves better performance gains over the former codebooks as well as lighter feedback overhead. And the number of spatial-frequency basis vectors $(L, M_v)$ play an important role in feedback overhead and performance. Note that more evaluation results under different parameter configurations can be found in [21], [22].

## VI. Port Selection Codebooks

A category of codebook called port selection codebooks is also supported in 3GPP standards, starting with Type II Port Selection Codebook introduced in R15. For ease of exposition, the codebooks discussed before are referred to as non-port selection codebooks in our paper. The main difference between the port selection codebooks and the previously described codebooks lies in the beam selection mechanisms. More specifically, in the non-port selection codebooks, the UE finds the spatial beams by computing the inner product between the DL CSI or precoders and the 2D DFT vectors with oversampling. One or several strong beams are then reported by the UE. In port selection codebooks however, the gNB transmits precoded reference signal (pilot) with different precoders, where each precoder represents a certain beam and is associated with an antenna port. The UE selects several antenna ports by pilot-based measurements and reports the corresponding coefficients. As a result, the beams are determined by antenna port selection. In port selection codebooks, all $N_{\mathrm{AP}}$ antenna ports are grouped by a port sampling parameter $d$. Then, the beam selection is indicated by a binary port choice.

Fig. 6 compares the differences between port selection codebooks and non-port selection codebooks.

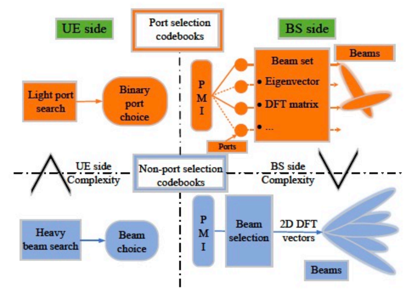


Fig. 6. CSI report of port selection codebooks and non-port selections codebook at the BS side and the UE side.

In general, the core idea of port selection codebooks lies in the fact that the UE reports a port selection decision other than a beam, and the UE is not aware of the specific beam related to a certain antenna port. After the gNB receives the reported port choice, it finds the beams corresponding to the selected antenna ports, and then reconstructs the DL precoder or CSI with the port-related quantized coefficients reported by the UE. Note that the beams are not limited to the 2D DFT vectors. It may also take the form of the eigenvectors of the channel covariance matrix, which generally outperforms the DFT vectors. Such kind of beams is enabled by the low-rankness property of the channel covariance matrix [23], [24], which facilitates the compression of the CSI using channel statistics.

The advantages of port selection codebooks are twofold. First, the form of beams is decoupled with the UE feedback. Hence, the topology of the antenna array at gNB is no longer limited to UPA and the beams are more flexible to accommodate different antenna typologies and algorithms. On the contrary, in non-port selection codebooks, the gNB and

the UE assume the beams to be 2D DFT vectors only, which may not work well under other antenna typologies than UPA. Second, the computation complexity is reduced at the UE side in exchange for extra beam calculation complexity at the gNB side. This is due to the binary port selection decision rather than the complex 2D beam searching procedure in non-port selection codebooks.

In 5G NR R17, three port selection codebooks are supported, i.e., Type II Port Selection Codebook, Enhanced Type II Port Selection Codebook and Further Enhanced Type II Port Selection Codebook, which will be discussed below.

### *A. Type II and Enhanced Type II Port Selection Codebook*

These two codebooks are proposed together with the corresponding non-port selection codebooks in R15 and R16, respectively. We focus on analyzing the port selection indicators of both codebooks.

First, the port sampling parameter $d$ is configured by the gNB. The indicator $i_{1,1}$ denotes the selected port sample group at each polarization. This indicator is different from the one in non-port selection codebooks. The value of $i_{1,1}$ varies from zero to $\lceil N_{\mathrm{AP}}/2d\rceil - 1$. The port selection index $q^{(i)}$ is mapped by $i_{1,1}$ as $q^{(i)} = i_{1,1}d + i$. Finally, the $q^{(i)}$-th entry of the reported port selection vector $\mathbf{w}_{q^{(i)}} \in \mathbb{C}^{\frac{N_{\mathrm{AP}}}{2}\times 1}$ is one and the rest are zero.

The remaining indicators and the precoding matrix calculation of these two codebooks are consistent with the corresponding non-port selection codebooks. Therefore, the PMI of these two codebooks can be obtained in a way similar to the corresponding non-port selection codebooks, and the details are omitted.

### *B. Further Enhanced Type II Port Selection Codebook*

This port selection codebook is first supported in the recent 5G NR R17. Its most intriguing characteristic lies in the exploitation of the partial angle-delay reciprocity of the channel in FDD massive MIMO. Even though the complete channel reciprocity does not hold in FDD, the frequency-irrelevant parameters, e.g., the multipath angle and delay distributions of the downlink and uplink channels are very close. Such a property is exploited in Further Enhanced Type II Port Selection Codebook and the feedback overhead is reduced. The core idea of Further Enhanced Type II Port Selection Codebook is elaborated in [17]. This codebook is enabled by a joint spatial-frequency domain precoding scheme for the transmission of the downlink CSI-RS. The joint spatial-frequency precoders are also referred to as “wideband precoders”. They are computed based on the uplink channel estimates, and the partial reciprocity is exploited therein. The choices of the wideband precoders can be flexible depending on different ways of implementation [17]. The specific form of wideband precoders includes, however not limited to, the DFT vectors and the eigenvectors of the joint spatial and frequency domain channel covariance matrix.

Thanks to the partial channel reciprocity, Further Enhanced Type II Port Selection Codebook has the potential to achieve better system performance with less feedback coefficients, and the computational complexity at the UE side is also greatly reduced.

Further Enhanced Type II Codebook extends the number of beams to $\alpha N_{\mathrm{AP}}/2$, where $\alpha$ is the ratio of the chosen antenna ports to the total antenna ports. The maximum reported beams is 6 according to Table 5.2.2.2.7-1 in [6]. However, in frequency domain, the number of frequency basis vectors $M_v \in \{1, 2\}$ is smaller than in Enhanced Type II Port Selection Codebook.

The PMI format of Further Enhanced Type II Port Selection Codebook is similar to Enhanced Type II Port Selection Codebook. However, it may report more beams compared to its predecessor. In frequency domain, the PMI report of Further Enhanced Type II Port Selection Codebook is quite different. Particularly, the frequency basis indicating vector $\mathbf{n}_3 \in \mathbb{C}^{1\times M}$ is defined like in Enhanced Type Port Selection Codebook, however it is identical across layers, rather than layer-dependent. A new indicator $i_{1,6}$ reflects the non-zero values of $\mathbf{n}_3$.

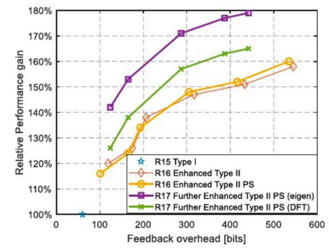


Fig. 7. The performance of Port Selection (PS) Codebook vs. feedback overhead, MU-MIMO, 32 ports, rank = 2, RU ≈ 70%.

According to the technical report [25], Further Enhanced Type II Port Selection Codebook is evaluated in terms of the relative throughput gains compared to the former codebooks in Fig. 7. Five parameter configurations of codebooks [6] are evaluated, except Type I Codebook. The numerical results demonstrate that Further Enhanced Type II Port Selection Codebook outperforms the other codebooks due to the exploitation of the partial reciprocity in the spatial-frequency domain. Moreover, the eigen-based Further Enhanced Type II Port Selection Codebook achieves a higher gain than the DFT-based one. For more details and simulation results of Further Enhanced Type II Codebook, one may refer to the technical reports [26], [27].

Generally speaking, port selection codebooks leads to a more flexible beam set than non-port selection codebooks. To be more specific, the beams can be chosen from DFT vectors, or the eigenvectors of covariance matrix, etc. It is not limited to a certain antenna array topology. On the contrary, the non-port selection codebooks generally assume a UPA or ULA topology at the gNB, and the beams are generated from

TABLE I
COMPARISON OF CODEBOOKS IN 5G NR R17

| Codebook type | Number of beams | Subband quantization manner | Feedback overhead | Complexity |
|---|---|---|---|---|
| Type I (Single-Panel) | 1 | phase | $\{2+N_3, 3+N_3\}$ | $\mathcal{O}(2N_1N_2\upsilon)$ |
| Type I (Multi-Panel) | 1 | phase | $\{6+N_3, 7+N_3, 8+N_3\}$ | $\mathcal{O}(2N_gN_1N_2\upsilon)$ |
| Type II | $\{2,3,4\}$ | phase and amplitude (1bit) | $2+\upsilon+(N_3+1)\sum_{l=1}^{\upsilon} M_{\mathrm{nz}}^l, I_s=0;$<br>$2+\upsilon+\sum_{l=1}^{\upsilon}(2N_3M_{\mathrm{vr}}^l+M_{\mathrm{nz}}^l), I_s=1$ | $\mathcal{O}(2\upsilon LN_1N_2)$ |
| Type II Port Selection | $\{2,3,4\}$ | phase and amplitude (1bit) | $1+\upsilon+(N_3+1)\sum_{l=1}^{\upsilon} M_{\mathrm{nz}}^l, I_s=0;$<br>$1+\upsilon+\sum_{l=1}^{\upsilon}(2N_3M_{\mathrm{vr}}^l+M_{\mathrm{nz}}^l), I_s=1$ | $\mathcal{O}(2\upsilon Ld)$ |
| Enhanced Type II | $\{2,4,6\}$ | phase, delay and amplitude (3bit) with compression | $2+\upsilon+2LM_\upsilon\upsilon+2M_{\mathrm{nz}}, N_3 \leq 19;$<br>$3+\upsilon+2LM_\upsilon\upsilon+2M_{\mathrm{nz}}, N_3 > 19$ | $\mathcal{O}(2\upsilon LM_\upsilon N_1N_2)$ |
| Enhanced Type II Port Selection | $\{2,4\}$ | phase, delay and amplitude (3bit) with compression | $1+\upsilon+2LM_\upsilon\upsilon+2M_{\mathrm{nz}}, N_3 \leq 19;$<br>$2+\upsilon+2LM_\upsilon\upsilon+2M_{\mathrm{nz}}, N_3 > 19$ | $\mathcal{O}(2\upsilon LM_\upsilon d)$ |
| Further Enhanced Type II Port Selection | $\{1,2,3,4,6\}$ | phase, delay and amplitude (3bit) with enhanced compression | $1+4LM\upsilon, N=2, \upsilon \leq 2;$<br>$1+2ML\upsilon+2M_{\mathrm{nz}}, N=2, \upsilon>2;$<br>$2+4LM\upsilon, N=4, \upsilon \leq 2;$<br>$2+2ML\upsilon+2M_{\mathrm{nz}}, N=4, \upsilon>2$ | $\mathcal{O}(2\upsilon L^2M)$ |

DFT vectors. However, the port selection codebooks require a more intelligent gNB algorithm to find the proper beams based on limited information, e.g., the partial reciprocity. In the non-port selection codebooks, since the UEs have the DL channel estimation, the beams are readily obtained with DFT transformations.

## VII. CODEBOOKS FOR THE FUTURE

In our previous discussion, we elaborated on the codebooks and the corresponding PMI report mechanisms of all codebooks supported in 5G NR so far. The key properties of these codebooks are summarized in Table I, which is a comparison in terms of the number of reported spatial beams, the subband coefficient quantization manner, the feedback overhead, and the computational complexity. Note that the feedback overhead is quantified by the number of all reported coefficients and indicators through all subbands. The complexity refers to the precoding matrix calculating complexity for the gNB.

In fact, different codebooks might be adopted according to different system requirements and application scenarios. Overall, the trade-off between performance and feedback overhead is the key point for codebook choice.

For example, in SU-MIMO, Type I Codebook may be sufficient due to its simplicity. And it performs well in simple wireless propagation environments, such as LOS scenarios. However, Type II Codebook and the succeeding codebooks support multiple beams and thereby may outperform Type I Codebook in MU-MIMO due to the better mitigation of multi-user interference. Moreover, in wideband massive MIMO, Enhanced Type II Codebook can effectively reduce the feedback overhead compared to Type II Codebook. In case of low feedback and complexity constraints at the UE side, port selection codebooks are more preferable than non-port selection codebooks. And port selection codebooks offer better flexibility in terms of the precoder form constraint and the BS antenna topology. Particularly, in wideband FDD massive MIMO, Further Enhanced Type II Codebook may be a better choice due to the reduced feedback overhead and increased system performance brought by the exploitation of partial channel reciprocity.

Nowadays, new multiple antenna technologies are emerging, and the application scenarios are extending. They call for suitable codebooks to accommodate specific scenarios and system requirements. In the following of the paper, we will discuss some unresolved challenges of codebooks for the future and some promising solutions to these challenges.

### A. Enhanced Codebook for mobile scenarios

One of the major challenges in massive MIMO is the mobility problem. The shorter coherence time in mobility scenarios leads to a serious degradation on the spectral efficiency [28]. Recently, some research work focused on this dilemma from the theoretical perspective [29]–[32]. In industry, the topic of mobility enhancement had been considered and discussed in R17 from the perspective of mobility management with a type of non-zero power (NZP) CSI-RS for mobility management, as well as synchronization signal block (SSB)-based handover between cells. In future R18 version or 5G-advanced, the enhancement of mobility performance will be an integral part and has been added to the agenda [33]. However in the 5G NR standards, no codebook has ever been particularly designed for the non-negligible UE mobility, which causes serious deterioration of the system spectral efficiency. The main reason lies in the fast variation of the channel, and in particular, the Doppler of the paths. Unfortunately, the codebooks supported in R17 cannot solve this challenge. They are not designed to characterize the Doppler frequency shift of the multipath of the channel, nor can they report timely CSI for high mobility scenarios.

In order to design an enhanced codebook for mobility scenarios, we believe that three constraints should be considered. First, the codebook should characterize the Doppler frequency shift information of the channel. Second, the time-varying channel demands a timely CSI feedback framework.

Introducing a channel prediction scheme in CSI report may be a solution. Third, the compatibility with the existing codebooks is also vital and will facilitate the implementation. The mobility enhanced codebook proposed in [34] is a candidate, which provides an effective approach to obtain the CSI in high mobility scenarios by applying a joint-angle-delay-Doppler (JADD) channel prediction scheme. The core idea is to track the multipath Doppler frequency shifts with a few channel samples. Moreover, the timely CSI feedback is enabled by a partial reciprocity based wideband precoding scheme for the pilots and the feedback-based CSI prediction at the gNB.

### B. Codebook for cell-free massive MIMO

Recently, a distributed multiple antenna system or cell-free massive MIMO system has drawn much attention by academia [35] and industry. Compared to cell-centric massive MIMO, cell-free massive MIMO aims to serve the UEs simultaneously through widely distributed access points (APs) instead of the centralized antenna array at the base station [36]. This cell-free massive MIMO mainly shows the advantage in exploiting diversity against shadow fading at the expense of high backhaul requirements. It may lead to performance improvements in respect of the coverage probability, the energy efficiency and the spectral efficiency [37].

In cell-free massive MIMO, the channel environments between the distributed APs and a certain UE are quite different. There is little correlation between the distributed BS antennas, which makes the CSI compression more challenging. In fact, the codebooks mentioned in this paper all rely on the channel structure, e.g., the spatial-domain structure of the multipath angular response and the frequency-domain structure of the multipath delay response. The structure makes the channel correlated and therefore compressible. In cell-free massive MIMO however, such structures are not available. Hence, it is more challenging to characterize the channel parameters of each path, and the current codebook framework may not be suitable for cell-free massive MIMO. Therefore, the major challenge of designing the codebook for cell-free massive MIMO lies in how to reduce the feedback overhead, which scales with the number of distributed antennas.

### C. Codebook for Ultramassive MIMO System

Nowadays, 6G is widely discussed and many emerging technologies are considered candidates to be used in 6G [38], [39], including ultramassive MIMO, which helps to meet the extremely high rate acquirement. One of the most tricky problem of ultramassive MIMO is the CSI acquisition due to the massive antenna arrays. We believe that the challenges are mainly reflected in the following three aspects. First, the channel propagation nature is coherently changed. Due to the increasing antenna dimension, the channel radiating environment tends to exhibit a near-field effect. Hence, current codebook which is based on far-field radiating condition may fail to characterize the channel environment. Second, the dimension of the CSI and the precoder increase significantly. Therefore, the complexity of precoding and signal processing in ultramassive MIMO increase exponentially. Third, future codebooks for ultramassive MIMO should be easy to implement in real communication system. Some state-of-the-art methods specialize in dealing with the overwhelming CSI, such as artificial intelligence (AI) [40], compressed sensing method [41], two-stage beamforming [42] and hybrid beamforming [43]. They are promising solutions to utramassive MIMO codebook design. Nevertheless, how these methods would be standardized and deployed in real communication systems is a problem that needs to be solved in the future.

## VIII. Conclusion

In this paper, we discussed the codebook evolution from the 3GPP standard point of view. We first summarized the timeline and trend of codebook evolution. The physical meanings of the codebook parameters were given for a better grasp on the codebooks. Then we elaborated on feedback scheme and the PMI format of all codebooks in 5G NR. We also compared the performance of the codebooks in respect of the number of supported beams, subband quantization and feedback manner, feedback overhead, and the complexity at the gNB. The numerical results of the performance vs. feedback overhead were given for different codebooks in 5G NR. Finally, the remaining issues of codebook design for high mobility scenarios were discussed, and the open problems of codebook for cell-free massive MIMO and ultramassive MIMO were raised.

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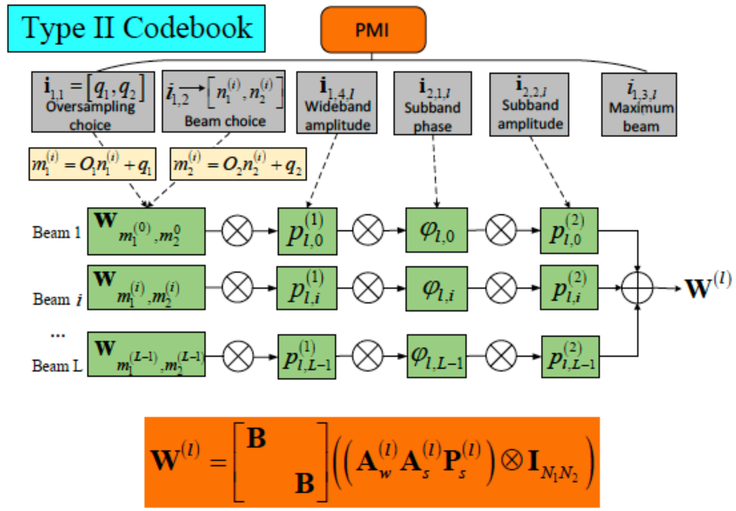
| |  Fig. 3. The PMI format and the precoding matrix of Type II Codebook at layer $l$. |

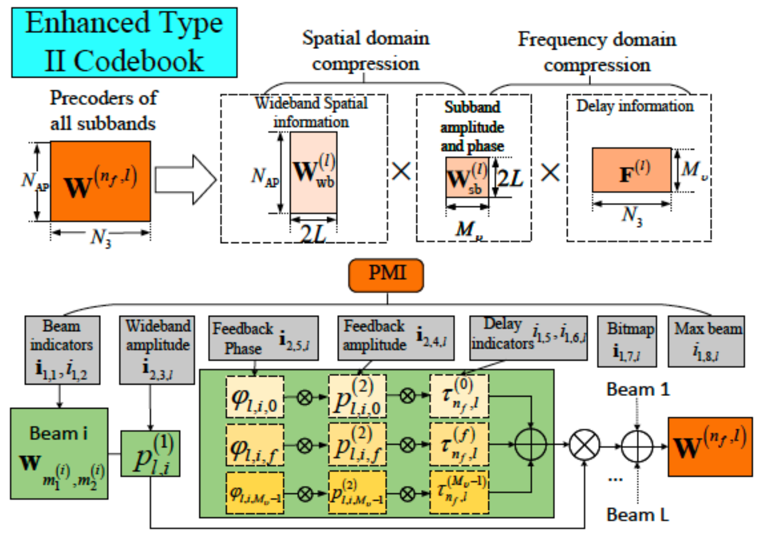



Fig. 4. The compression in spatial and frequency domain and the PMI format of Enhanced Type II Codebook.

For example, Ericsson published "How to build high-performing Massive MIMO systems," Billy Hogan, Bo Göransson, Sebastian Faxér, Sibel Tombaz, available athttps://www.ericsson.com/en/blog/2021/2/how-to-build-high-performing-massive-mimo-systems. This article explains that Massive MIMO solutions or advanced antenna systems (AAS) with beamforming features comprises an AAS radio and Massive MIMO features such as beamforming which can be executed by algorithms in the AAS radio or a RAN Compute connected to the AAS radio or both. It further describes the use of channel estimation to understand multipath transmission delay and reshape beams in both time and frequency to modify the transmission power level of multiple OFDM tones:

"Of course, just being able to focus energy in a fixed direction is not very useful as people typically move around. So, to be able to control the direction and shape of the beams in

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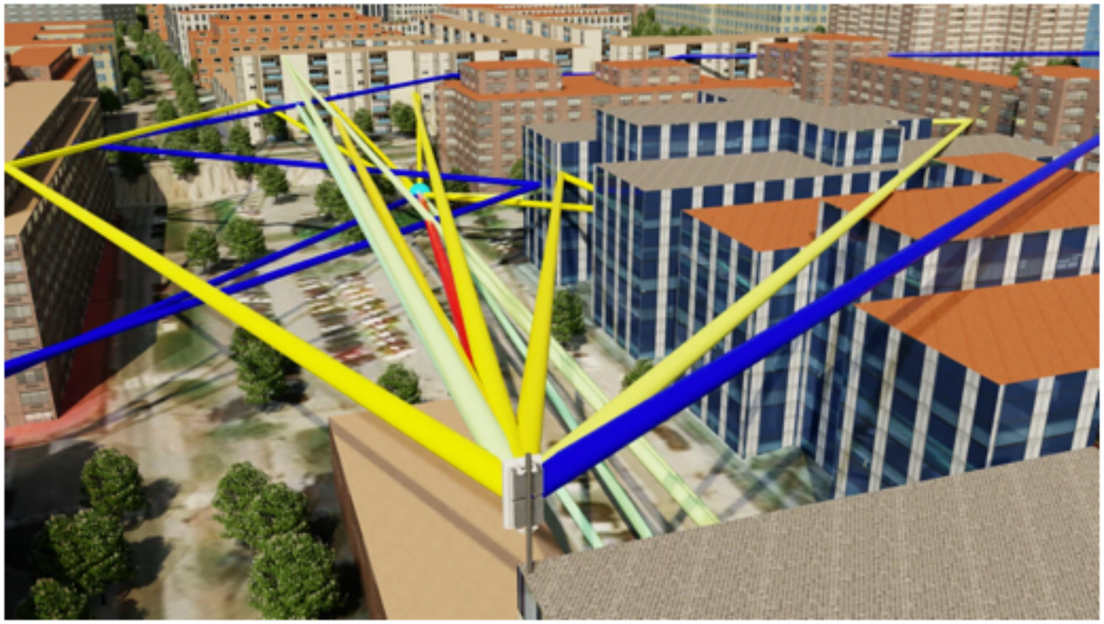
| | any way we want in space, we also make the antennas individually controllable with their own radio chains, so we can change the amplitude and phase of their signals separately.<br><br>This gives us numerous coverage and capacity abilities, including:<br><br>• To create multiple beams at the same time<br>• To send and receive radio signals extremely quickly – on a fraction of a millisecond basis – where we want to, while reducing interference in directions where we don´t want that energy to go or come from. All of this, for multiple users simultaneously!<br><br>But - this is no easy task. How do we “form” the right beams to get the most signal energy to the user that we want? People usually think of a beam as a simple concentration of energy that looks like the figure below. You just point it in the direction that you want and that´s all that you need. It is true that you can form beams like that, and they will often work quite well, but they are not always optimal.<br><br>The reason we can do better than a simple beam is that the “radio channel” is a highly complicated environment, since the signal path that travels between the base station and each device reflects off numerous objects causing standing waves and dips that change in time and in frequency at sub millisecond level, as multiple paths arrive at the receiver from all directions, as illustrated in the picture below. |



Think of a choppy ocean… what should the ideal beams look like to navigate this environment with the best performance? To add to the complexity, this channel is different for each of the hundreds of moving devices that are connected within a cell so they each need precisely created beams of their own and of course when we send a beam to one user we don't want to interfere with others.

So, the beams must be highly precise, individual, and continually reshaped every fraction of a millisecond both in time and frequency, based on instant measurements of the radio channel across the spectrum together with large scale calculations to work out and apply the beams to the data we want to send or receive. The gigabits of data that are sent and received over the air interface are practically surfing the radio channel and just as in wave surfing, precise timing is essential to catch the radio waves. If you let your view of the channel information get too old, which happens extremely quickly, you will fall off the wave, and miss the chance to optimize your beamforming

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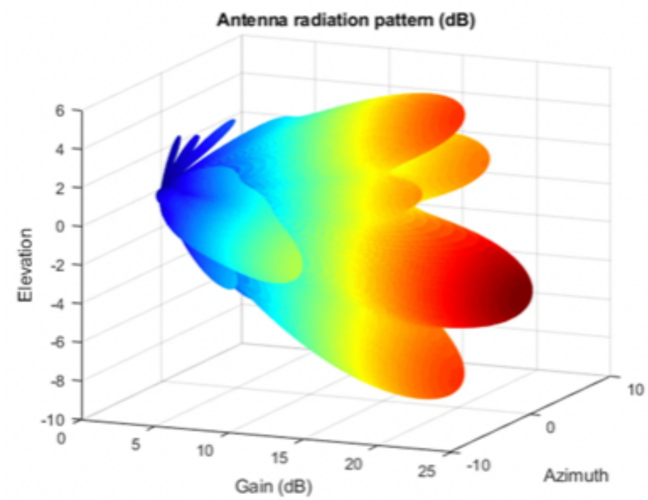
| | performance. The instantaneous beam that works best can look quite arbitrary as illustrated below but best achieves the goal of getting the energy exactly where we want until we change it for a new beam a fraction a millisecond later.<br><br><br><br>For CSPs, the result is much greater coverage, much greater network capacity and high end-user speeds over a wider area compared to remote radio unit solutions. The CSP can exploit their valuable spectrum resources to the utmost without vastly increasing the number of sites. This has the benefit of reducing the cost per gigabit per area while preparing CSPs for future traffic growth - they can continue providing outstanding speeds and great coverage as the data traffic load gets heavier.<br><br>**The art and science behind Ericsson Advanced Antenna Systems**<br>We can clearly see the benefits of AAS. However, there are also challenges to realize its full potential:<br><br>• **Radio challenges:** Larger bandwidth and more antenna branches drive the need for increased processing capacity, which drives higher power consumption, size and weight at the base station. |

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| | • **Beamforming challenges:**<br>  ◦ The radio environment changes on sub-millisecond timeframes as the smartphone moves. Adding to this complexity is of course the hundreds of other devices that connect within the cell.<br>  ◦ The beams must be continually reshaped every fraction of a millisecond, based on instant snapshots of the channel, both in time and frequency.<br>  ◦ To adapt the beams in a complex radio environment for many users simultaneously when using multiple antennas, requires millions of mathematical calculations per second<br><br>To address these challenges, Ericsson adds three key components: **access** to information about the instantaneous radio channel, clever **algorithms** which utilize this information, and the processing power of the Ericsson **silicon**. Fortunately, Ericsson's long experience in the AAS field has ensured that both our hardware design and beamforming algorithms are prepared for this.<br><br>The Ericsson Massive MIMO architecture has been designed to put as much as possible of the beamforming and MIMO processing in the AAS radio itself, close to the antennas and radio channel, where we have **access** to real-time and fine granular information about the radio channel.  Therefore, Ericsson is able to do channel estimation and beamforming weight calculations that follow the extremely rapid changes that occur on the radio channel almost instantaneously. You could say that Ericsson Massive MIMO antennas have a fingertip feel of the radio channel and can react to the real-time channel situation with the best possible beams.<br><br>Putting this processing in the radio where it belongs also has other advantages. The fronthaul bit rate from the radio to the RAN Compute is reduced, thus saving costs, and the RAN Compute can concentrate on its own tasks,- for example to schedule users over many cells, and to encode and decode the data bits on the user plane, which must be well protected before they are sent over the air. |

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| | Secondly, we need clever beamforming **algorithms** to act on the channel data. In fact, the way to do the beamforming in 5G is not defined by any 3GPP standard and is completely up to implementation, which means there is a lot of room for innovation and artistic freedom.<br><br>To solve the complex challenge of adapting to time-varying radio channel, we need to generate ultra-precise beamforming by applying different precoder weights to the antenna elements of our array so that after passing through the wireless channel to the target user, the signals from the multiple antennas add up coherently to boost the signal. This is analogous to creating a harmony in music by playing several tones on the piano at certain specific intervals so that when added up they form a pleasant-sounding chord.<br><br>But we simultaneously want to reduce interference to other users by having the signals from the different antenna elements add up destructively, akin to creating a dissonant-sounding chord in music by playing tones with other intervals (like a diminished fifth). The problem to generate optimal beamforming performance to achieve these goals simultaneously then becomes similar to composing a musical arrangement with complex harmonies and passages, while handling multiple instruments simultaneously, both an art and a science! And as we know, it takes both skill and dedication to become a Mozart as it does to master the art of Massive MIMO.<br><br>To generate ultra-precise beamforming, a massive set of complex calculations needs to be performed in real-time, scaling with the number of antennas, the bandwidth and number of users. This adds up to millions of mathematical calculations per second, which requires an extreme processing capability. In addition, it also requires our sophisticated software features and algorithms to make sure that we leverage that hardware in the best way. This can only be achieved with Ericsson **silicon,** system on a chip (SoC) solution, as outlined in the previous blog. It can not only handle all that processing capacity inside the Massive MIMO radio, but also creates much tighter |

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| | integration of components inside the radio. This way, we can build a high-performing radio without adding size, weight or energy consumption.<br><br>As another example, 5G NR beamforming technology is described in secondary sources, such as “MIMO Beamforming Using PMI Type II Precoding,” Caroline Jenisha Ruth Mary Pramila Paul Sudhakar, Degree Project in Electrical Engineering, Second Cycle, Stockholm, Sweden 2021, KTH Royal Institute of Technology, available at https://www.diva-portal.org/smash/get/diva2:1618389/FULLTEXT01.pdf. This project lists Carolina Jenisha R P of KTH Royal Institute of Technology as Author with Ericsson AB as Host Company, Medhat Mohammad of Ericsson AB as Supervisor, and Ben Slimane of KTH Royal Institute of Technology as Examiner.<br><br>**2.2.1 Beamforming**<br><br>Focusing the power of all antenna elements combined with the help of beamformers or weights towards one direction is called beamforming as shown in figure 2.2.1. When the angular spread between the BS and UE is zero (i.e.) in the existence LOS or one dominant path the above definition applies. In reality, there exists multiple paths (i.e.) NLOS or multiple paths, which requires *precoding* at the transmitter or receiver. Precoder applies weights on to the antenna element that comprises of amplitude and phase for each antenna element. With the help of weights, the antenna can be electronically steered to radiate in the intended direction by suppressing the power in the other directions. Beamformers can be precoded to radiate in two or more propagating path making use of the diversity gain provided by the fading channel. In general, BF can be considered as a special case of precoding for LOS path. The precoded data is spatially combined and transmitted.<br><br>When BF is implemented at the the receiver added to BF at the transmitter provides<br><br>CHAPTER2. THEORETICAL CONCEPTS AND RELATED WORK |

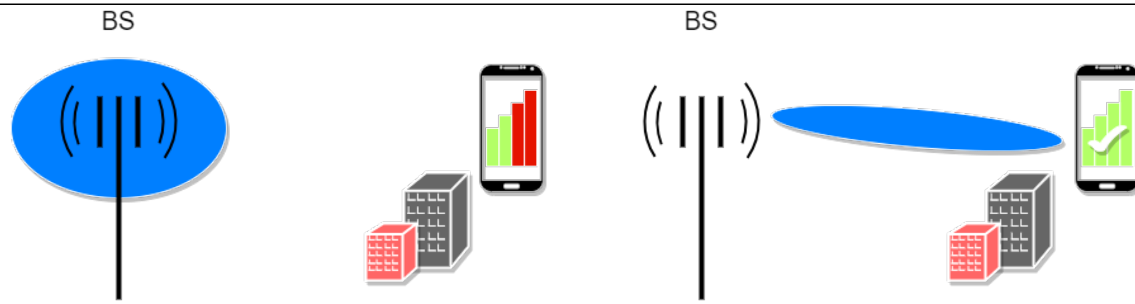


Figure 2.2.1: Compared to the BS with isotropic radiation (left) and BS that performs beamforming (right), the signal strenght of beamformed signal increases directivity towards the user which increases the received power thereby increasing the links data rate.

both array gain and diversity gain. As the number of antenna elements increases at the receiver, increases the average Signal to Noise Ratio (SNR) achieved by coherently combining all the antenna elements on the other hand diversity gain helps to increase the instantaneous SNR at the receiver by selective coherent combining of different antenna elements experiencing different fading pushing the combined SNR more concentrated towards the average SNR [11].

### 2.2.2 Spatial Multiplexing

The procedure beamforming when applied to different data streams can be spatially multiplexed in one time and frequency resource. The multipaths provided by MIMO is essentially used to improve the data rate of the UE. This can be visualised in two different scenarios as shown in figure 2.2.2.

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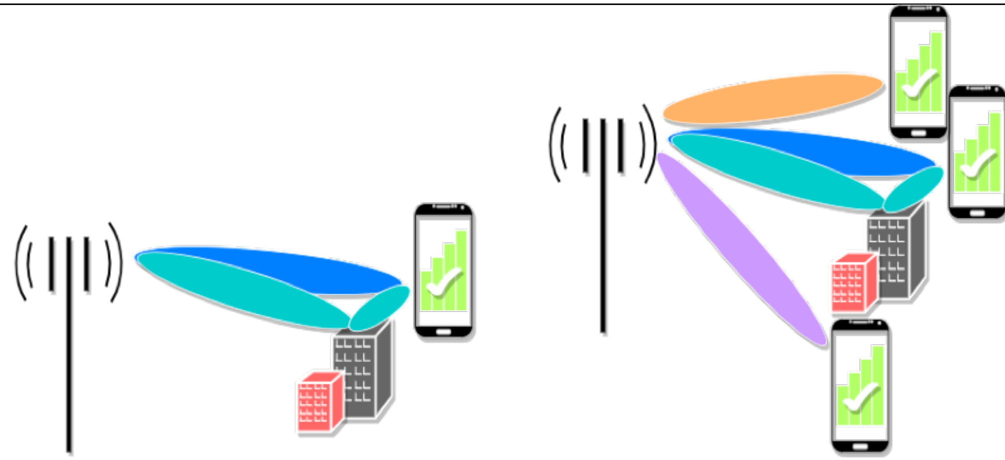
| |  Figure 2.2.2: Spatial multiplexing seen in SUMIMO(left) and MUMIMO(right).<br><br>**2.3 CSI reporting**<br><br>The BS requires a pretext before transmitting data to the respective user. This pretext is referred to the information about channel observed from the direction of the user. CSI report is considered as a feedback from UE that carries the channel information which helps in designing the precoder or choosing the optimum precoder in case of codebook based precoding.<br><br>**2.3.1 Beam Management**<br><br>CSI acquisition is done in two stages. The first stage is Beam Management (BM) where the UE measures the Reference Signal Received Power (RSRP) of the set of analog beams transmitted by the BS and reports the beam ID of the best beam to the BS [9]. NR DL measurements for BM include Synchronization Signals (SS) bursts and Channel State InformationReference Signals (CSIRS) or NR Uplink (UL) measurements for BM |

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| | include Sounding Reference Signals (SRS) as shown in figure 2.3.1. In BM based CSIRS, a set of analog beams is sent by BS to UE and the UE reports the CSI to the BS [8]. On the other hand, in BM based SRS, channel measurements are sent by the UE via a set of analog beams and received by BS. BS selects the best analog beams after measurements based on channel reciprocity where angle of arrival becomes the angle of departure of analog beams [8]. This holds, for instance, if the UE has the ability to transmit and receive with the same number of antennas as in Time Division Duplexing (TDD) [9]. However, UEs may use a different number of antennas for transmission and reception where channel reciprocity could not be met. Additionally, SRS based BM is more suitable for linear precoders as the precoder matrix requires detailed CSI whereas CSI-RS based BM is more suitable for GoB precoders. According to 5G standardization, BM in general consists of beam sweeping, beam measurement, beam determination, beam reporting , beam maintenance and beam recovery [8, 9]. These procedures are repeated to update the links periodically.<br><br>**2.3.2 PMI report**<br><br>The first stage is followed by the second stage, namely CSI acquisition report from the UE. After the NR DL or UL BM measurements, the BS assigns a subset of analog beams towards that UEs location and the UE generates the CSI report and sends the report to the BS [8]. The CSI report contains, |

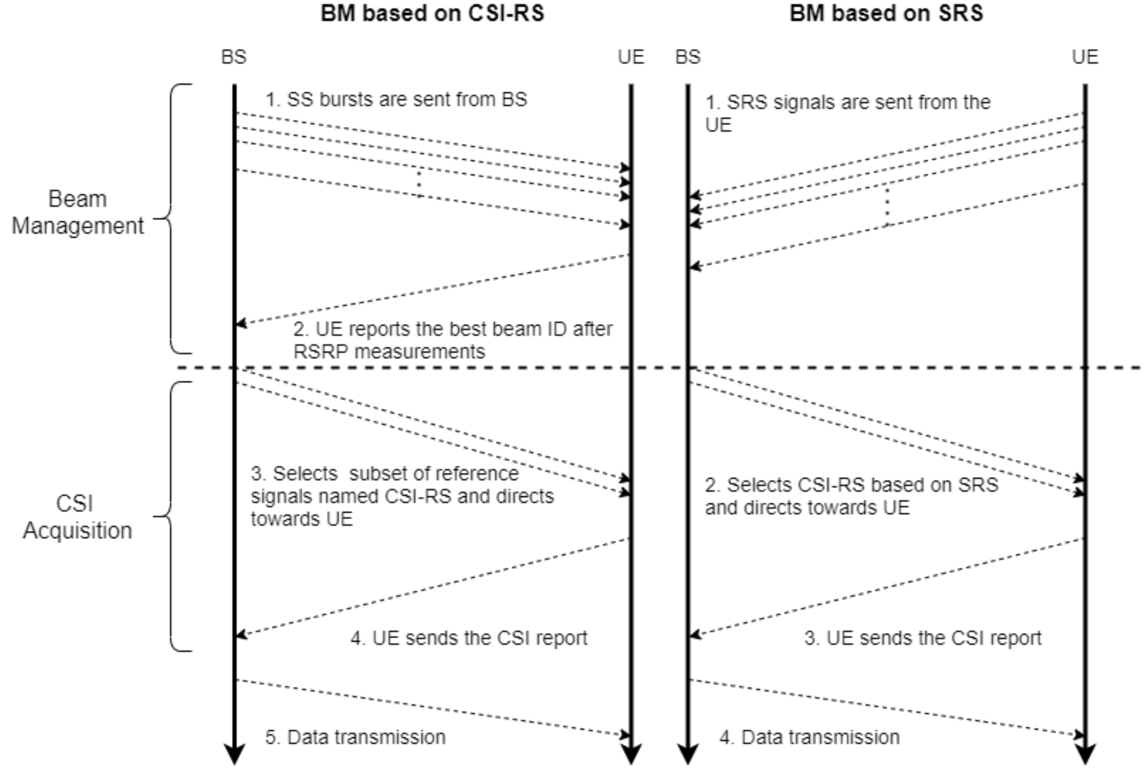


Figure 2.3.1: Beam Management procedures

• *Rank Indicator (RI)*, used to indicate the preferred number of transmission layers.

• *Precoder Matrix Indicator (PMI)*, used to indicate preferred design of precoder matrix for the given rank.

• *Channel Quality Indicator (CQI)*, used to indicate the suitable channelcoding rate and modulation scheme for the given PMI. [2].

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| | The PMI values corresponding to the different precoder matrix is chosen from the precoder codebook defined by the standards . Despite the CSI report sent by the UE, the network can choose any precoder matrix design for data transmission. Although choosing the precoder design preferred by UE makes sense, in many cases that is not entirely possible especially in MUMIMO [10]. Therefore, NR defines two different types of CSI that differ in size and structure of the precoder matrix. *Type I CSI* (standard/low resolution) is predominantly used for SUMIMO scenarios as it relies on the UE to suppress the interference due to the different layers. This is due to the fact that the number of layers will never be larger than the number of receiver antennas. On the other hand, *Type II CSI* (high resolution) is primarily used for MUMIMO and is limited to a smaller number of layers (maximum of two). Since the number of received streams is larger than the number of receiver antennas, the interference is managed by the BS with the help of BF or precoder design [9].<br><br>See also "Chapter 3: Methodologies," which is incorporated by reference herein.<br><br>5G NR beamforming is also described in secondary sources, such as Ziao Qin and Haifan Yin, "A Review of Codebooks for CSI Feedback in 5G New Radio and Beyond," submitted, February 2023, 10.48550/arXiv.2302.09222, available online: https://arxiv.org/abs/2302.09222, also available at https://www.researchgate.net/publication/368665066_A_Review_of_Codebooks_for_CSI_Feedback_in_5G_New_Radio_and_Beyond<br><br>5G NR beamforming is also described in secondary sources, such as on the NR Cell Performance Evaluation with MIMO page on https://www.mathworks.com/help/5g/ug/nr-cell-performance-evaluation-with-mimo.html. This explains that:<br><br>**NR Cell Performance Evaluation with MIMO**<br><br>This example models a 5G New Radio (NR) cell with multiple-input multiple-output (MIMO) antenna configuration and evaluates the network performance. You can customize the scheduling strategy to leverage the MIMO capabilities and analyze the performance. This example performs downlink (DL) and uplink (UL) channel measurements using multi-port channel state information reference signals (CSI-RS) |

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| | and sounding reference signals (SRS), respectively. The gNB uses the measured channel characteristics to make MIMO scheduling decisions.<br><br>**Introduction**<br><br>MIMO improves network performance by improving the cell throughput and reliability. The example performs layer mapping and precoding to utilize MIMO in the DL and UL directions.<br><br>This example models:<br><br>• Single-codeword DL spatial multiplexing to perform multi-layer transmission. Single-codeword limits the number of transmission layers to 4.<br>• Single-codeword UL spatial multiplexing. The 3GPP specification allows only single-codeword in UL direction which limits the number of transmission layers to 4.<br>• Precoding to map the transmission layers to antenna ports. The example assumes one-to-one mapping from antenna ports to physical antennas.<br>• DL channel quality measurement by UEs based on the multi-port CSI-RS received from the gNB. The same CSI-RS configuration applies to all the UEs.<br>• UL channel quality measurement by gNB based on the multi-port SRS received from the UEs. The example does not support UL rank estimation and provides the rank to be used for estimating UL precoding matrix as a configuration parameter.<br>• DL rank indicator (RI), precoding matrix indicator (PMI), and channel quality indicator (CQI) reporting by UEs. The example supports Type-1 single-panel codebook for PMI.<br>• Free space path loss (FSPL), additive white Gaussian noise (AWGN), and clustered delay line (CDL) propagation channel model.<br><br>Nodes send the control packets (buffer status report (BSR), DL assignment, UL grants, PDSCH feedback, and CSI report) out of band, without the need of resources for transmission and assured error-free reception.<br><br>**MIMO**<br><br>The key aspects of MIMO include spatial multiplexing, precoding, channel measurement and reporting. |

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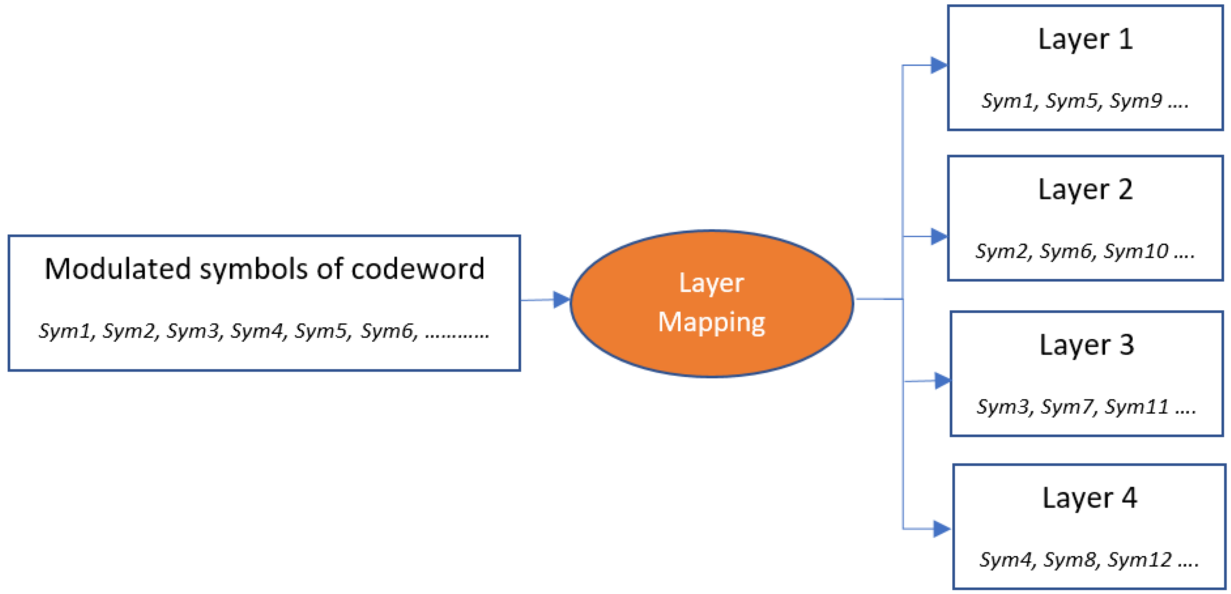
| | *Spatial multiplexing*   Spatial multiplexing utilizes MIMO to perform multi-layer transmission. The minimum of number of transmit and receive antennas limits the number of layers (or maximum rank). The layer mapping process maps the modulated symbols of the codeword onto different layers. It maps every $n_{\mathrm{th}}$ symbol of the codeword to $n_{\mathrm{th}}$ layer. For instance, this figure shows the mapping of a codeword onto four layers. Furthermore, in the DL direction, NR specification also allows two codewords and up to a maximum of 8 transmission layers. The example currently only supports single codeword for both DL and UL.<br><br>*Precoding* |

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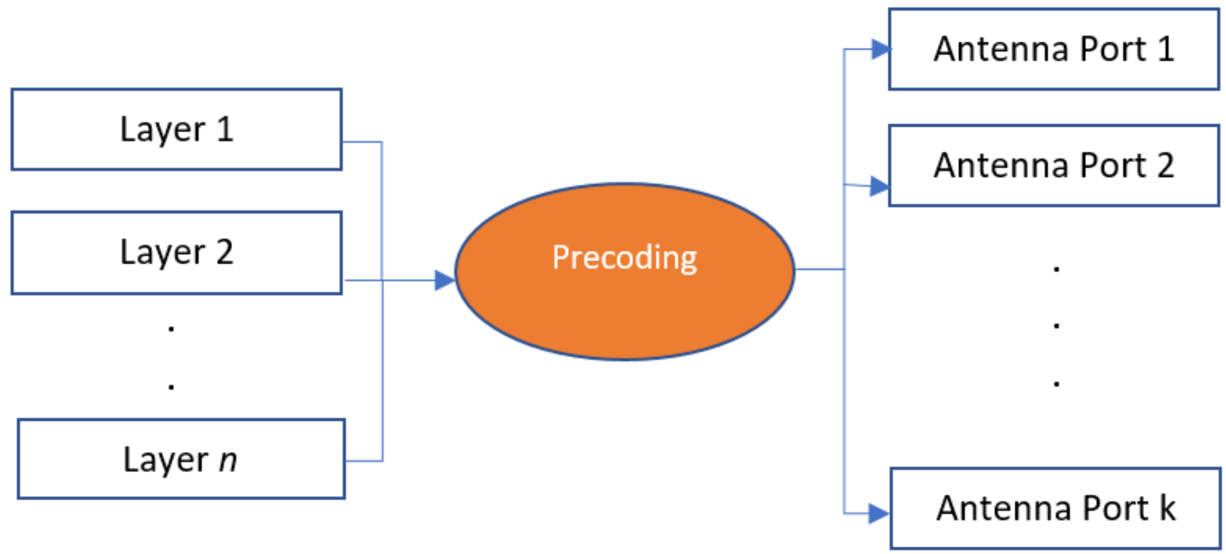
| |  <br>Precoding, which follows the layer mapping, maps the transmission layers to antenna ports. Precoding applies a precoding matrix to the transmission layers and outputs data streams to the antenna ports.<br>*Channel measurement and reporting*<br>It consists of DL channel measurement and reporting by the UEs and UL channel measurement by gNB. |

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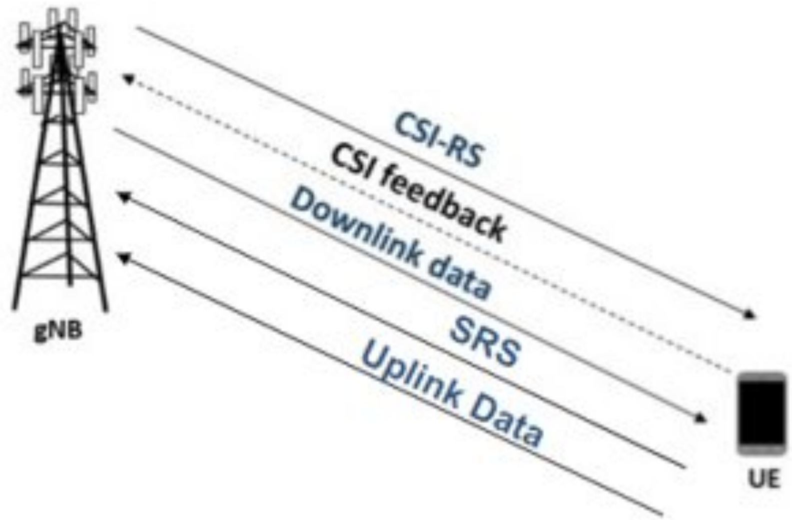
| | <br>*DL channel measurement and reporting*<br>CSI reporting is the process by which a UE, for DL transmissions, advises a suitable number of transmission layers (rank), PMI, and CQI values to the gNB. The UE estimates these values by performing channel measurements on its configured CSI-RS resources. For more details, see the 5G NR Downlink CSI Reporting example. The gNB scheduler uses this advice to decide the number of transmission layers, precoding matrix, and modulation and coding scheme (MCS) for PDSCHs.<br>*UL channel measurement*<br>gNB uses SRS to measure UL channel characteristics in a way analogous to CSI-RS based DL channel measurements. The UL channel measurements serve as an important input to the scheduler to decide the number of transmission layers, precoding matrix and MCS for PUSCHs. |
| 1[c] modifying a forward path data signal that is to be transmitted to the receiving device based on said at least one forward path pre-equalization parameter, where said modifying includes selectively setting different transmission power | Each accused product performs a method comprising 1[c] modifying a forward path data signal that is to be transmitted to the receiving device based on said at least one forward path pre-equalization parameter, where said modifying includes selectively setting different transmission power levels for at least two Orthogonal Frequency Division Multiplexing (OFDM) tones in |

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| levels for at least two Orthogonal Frequency Division Multiplexing (OFDM) tones in said forward path data signal. | said forward path data signal. Each of the descriptions and evidence in the charts above is incorporated by reference here.<br><br>Ericsson and Nokia RAN solutions use beamforming for 5G communications. For example, data symbols of a data stream/layer in a MIMO transmitter are modified by applying a set of coefficients to the said data to form at least one spatial beam. The modification is carried out using the beamformer coefficient parameters ("pre-equalization parameter"), also known as precoder in 3GPP. The beamformer coefficients/precoder parameters ("pre-equalization parameters") are computed using e.g. the channel frequency response, channel impulse response, amplitude offset, phase offset, complex numbers determined with channel estimation ("multipath delay"). The parameters depend on the channel frequency response. In a frequency selective (multipath) radio propagation channel, the channel frequency response is different on the different frequency tones of the OFDM signal. Therefore, the precoder/beamformer coefficient parameters applied to the symbols of the different tones are different to accommodate the differences in the channel frequency response on the different tones due to multipath. In 5G, frequency/time resources consist of frequency tones of the OFDM symbols. The allocated resources to a device, so called resource grid, consist of multiple Resource Blocks (RBs), and each RB in turn consists of 12 frequency tones. Therefore, the frequency tones of a resource grid cover a range of frequency spectrum, over which the channel frequency response varies, requiring different beamformer coefficient/precoder parameter for different tones. The beamformer coefficient/precoder parameters are complex numbers whose amplitude determines the amount of power applied to the tones. For example, the precoding parameters selectively set different transmission power levels for at least two tones, including, for example, in the examples described above for TDD (e.g., using SRS to identify the multipath transmission delay and determine forward path pre-equalization parameter) and in the examples described above for FDD (e.g., using CSI measurements such as PMI to identify multipath transmission delay and determine forward path pre-equalization parameter, such as with regard to Type II or Enhanced Type II Codebook).<br><br>For example, for TDD or FDD, the Ericsson and Nokia RAN Solutions receive SRS from the user equipment, identify at least one multipath transmission delay in the SRS, determine beamforming precoding coefficient parameters based on identifying at least one multipath transmission delay in the SRS, and apply the beamforming precoding coefficient parameters to downlink transmissions to selectively set different transmission power levels for at least two OFDM tones. As another example, for TDD or FDD, the Ericsson and Nokia RAN Solutions |

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| | receive a CSI report in response to CSI-RS with PMI, identify at least one multipath transmission delay within the received signal, and accordingly determine beamforming precoding coefficient parameters based on the channel estimate and apply them to downlink transmission to selectively set different transmission power levels for at least two OFDM tones. Beam amplitude scaling is supported for these and other non-limiting examples described herein. As described above for 1[b], for example, in e.g. TDD systems, the multipath transmission delay identified by the gNB using the received SRS symbols, is, by taking advantage of channel reciprocity property of a TDD system, used by the gNB to compute a set of beamforming coefficient parameters ("pre-equalization parameter") that are used for precoding, much like PMI parameters in e.g. FDD systems. These pre-equalization parameters are, as in the PMI approach, applied to the data stream to form a downlink beam. For example, in a TDD system (where UL and DL channels are considered reciprocal), an Ericsson and/or Nokia base station calculates DL precoding weights based on the sounding reference signal that a user transmits in UL. As another example, in downlink beamforming in e.g. FDD systems, the Ericsson and/or Nokia gNB base station expects that the user equipment device makes Channel State Information (CSI) measurements such as the Precoding Matrix Indicator (PMI) and transmits the PMI to the gNB. The gNB receives the CSI measurements such as PMI in a reverse path data signal received from the user equipment device. The gNB identifies at least one multipath transmission delay in the reverse path data signal (e.g., the CSI measurements such as, e.g., PMI). The gNB determines at least one forward path pre-equalization parameter based on the transmission delay. For example, PMI is an index to a set of coefficients ("forward path pre-equalization parameter") that are applied to the data stream to e.g. form a beam toward the device. The base station determines the DL precoding weights / coefficients to apply based on the identified multipath transmission delay.<br><br>As yet another example, the Ericsson and/or Nokia RAN Solutions may use analog beamforming or combination of analog and digital beamforming. For example, the RAN Solution also identifies at least one multipath transmission delay in a reverse path data signal when determining antenna array element coefficients by evaluating signals received on the elements of the array. The base station determines at least one forward path pre-equalization parameter (e.g., analog domain and digital domain coefficients / complex numbers (e.g., amplitude, phase) channel parameters, e.g., for beamforming or MIMO, that are applied to downlink transmission signals) based on identifying the multipath transmission delay. These forward path pre-equalization parameters (e.g., analog domain and digital domain coefficients / |

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| | complex numbers (e.g., amplitude, phase) channel parameters, e.g., for beamforming or MIMO, that are applied to downlink transmission signals) selectively set different transmission power levels for at least two OFDM tones.<br><br>See https://www.sharetechnote.com/html/5G/5G_CSI_RS_Codebook.html:<br><br>**What is Codebook ?**<br><br>What is Codebook ? It would many different things in different situation, but the meaning of Codebook under the context of CSI-RS is a set of Precoders (a set of Precoding Matrix). Putting it other way, Codebook is a kind of matrix (a matrix having complex value elements) that transform the data bit (PDSCH) to another set of data that maps to each antenna port.<br>… |

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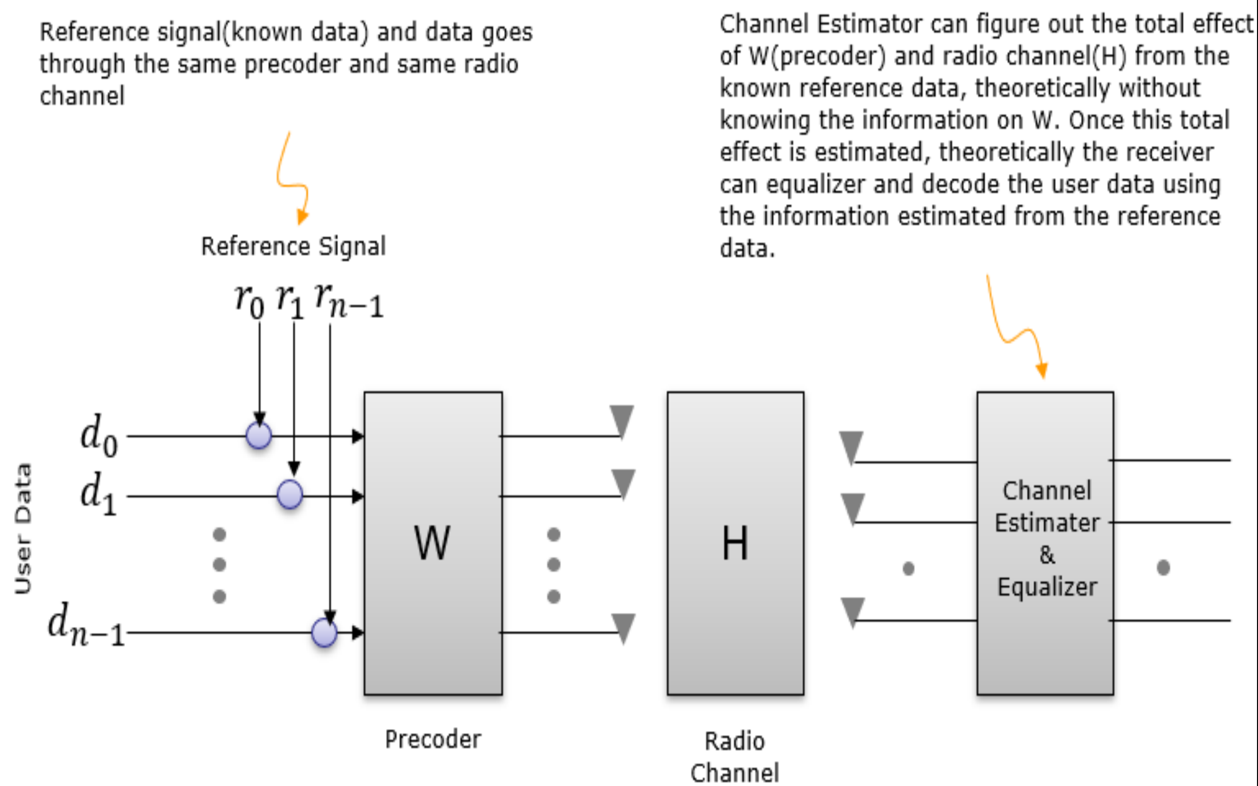
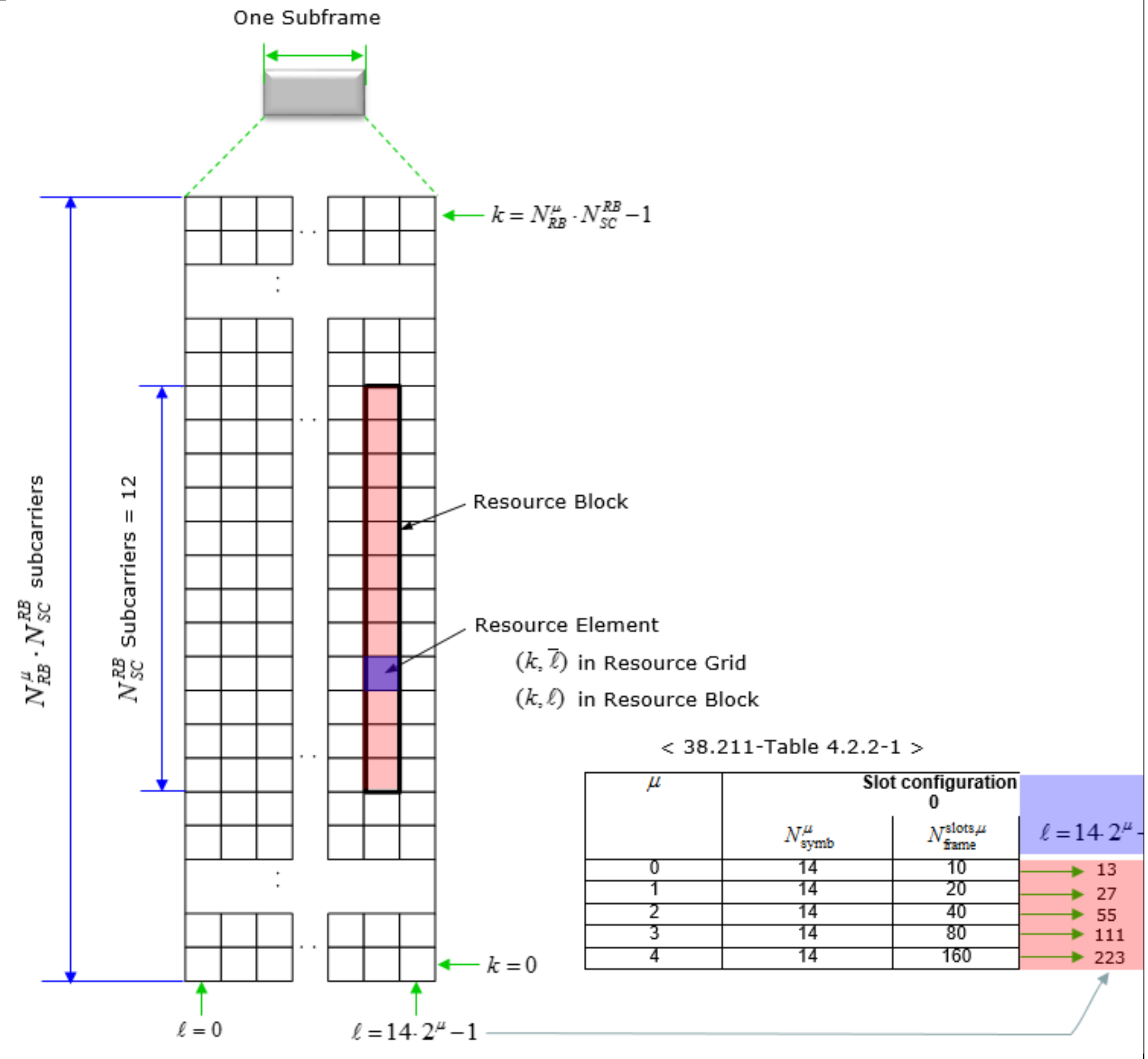
| | <br>See https://www.sharetechnote.com/html/5G/5G_ResourceGrid.html:<br>**Resource Grid**<br>The resource grid for NR is defined as follows. If you just take a look at the picture, you would think it is almost identical to LTE resource grid. But the physical dimension (i.e., subcarrier spacing, number of OFDM symbols within a radio frame) varies in NR depending on numerology. |




| $\mu$ | Slot configuration 0 | | $\ell = 14 \cdot 2^{\mu}$ - |
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| | $N_{\text{symb}}^{\mu}$ | $N_{\text{frame}}^{\text{slots},\mu}$ | |
| 0 | 14 | 10 | 13 |
| 1 | 14 | 20 | 27 |
| 2 | 14 | 40 | 55 |
| 3 | 14 | 80 | 111 |
| 4 | 14 | 160 | 223 |

**Resource Element** : This is same as LTE. It is the smallest unit of the resource grid made up of one subcarrier in frequency domain and one OFDM symbol in time domain.

**Resource Block**: In NR, Resource Block is defined only for frequency domain. 38.211-4.4.4.1 states *'A resource block is defined as 12(N_RB_sc) consecutive subcarriers in the frequency domain'*.
Time domain definition of resource block is a little bit ambiguous. Minimum time domain length in a resource block can be one OFDM symbol, but exact time domain length vary depending SLIV.

**Resource Grid and Antenna port and Numerology** : Basically one resource grid is created for one antenna port and numerology. 38.211-4.2.2 states as follows.

- *There is one set of resource grids per transmission direction (uplink or downlink) with the subscript set to DL and UL for downlink and uplink*
- *There is one resource grid for a given antenna port p , subcarrier spacing configuration u, and transmission direction (downlink or uplink).*

The maximum and minimum number of Resource blocks for downlink and uplink is defined as below (this is different from LTE)

< 38.211 Table 4.4.2-1: Minimum and maximum number of resource blocks.>

| $\mu$ | $N_{RB,DL}^{min,\mu}$ | $N_{RB,DL}^{max,\mu}$ | $N_{RB,UL}^{min,\mu}$ | $N_{RB,UL}^{max,\mu}$ |
|---|---|---|---|---|
| 0 | 24 | 275 | 24 | 275 |
| 1 | 24 | 275 | 24 | 275 |
| 2 | 24 | 275 | 24 | 275 |
| 3 | 24 | 275 | 24 | 275 |
| 4 | 24 | 138 | 24 | 138 |

The Ericsson 5G NR RAN Solution is described as an the Ericsson Advanced Antenna Systems for 5G in the Ericsson White Paper on Advanced Antenna Systems for 5G Networks (publication, including contributors Peter von Butovitsch, David Astely, Christer Friberg, Anders Furuskär, Bo Göransson, Billy Hogan, Jonas Karlsson and Erik Larsson). The transceiver coupled to the smart antenna and to the processor and configured to transmit the

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| | probing signal is satisfied by the active antenna system products: See https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks (also available at https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks):<br><br>See, e.g., Ericsson Advanced Antenna System for 5G Networks white paper / https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks:<br><br>***Key terms***<br>**AAS radio** = Hardware unit that comprises an antenna array, radio chains and parts of the baseband, all tightly integrated to facilitate AAS features<br>**AAS feature** = A multi-antenna feature (such as beamforming and MIMO) that can be executed in the AAS radio, in the baseband unit or both<br>**AAS** = AAS radio + AAS features<br>**Conventional system** = Passive antenna + remote radio unit comprising a low number (2, 4 or 8) of radio chains<br>**Dual-polarized antenna element** = Combination of two antenna elements with orthogonal polarizations with the purpose of enabling diversity and doubling the number of antenna elements on a given physical area<br><br>**What is an advanced antenna system?**<br>An advanced antenna system (AAS) is a combination of an AAS radio and a set of AAS features. An AAS radio consists of an antenna array closely integrated with the hardware and software required for transmission and reception of radio signals, and signal processing algorithms to support the execution of the AAS features. Compared to conventional systems, this solution provides much greater adaptivity and steerability, in terms of adapting the antenna radiation patterns to rapidly time-varying traffic and multi-path radio propagation conditions. In addition, multiple signals may be simultaneously received or transmitted with different radiation patterns.<br><br>***Multi-antenna techniques***<br>Multi-antenna techniques, here referred to as AAS features, include beamforming and MIMO. Such features are already used with conventional systems in today's LTE |

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| | networks. Applying AAS features to an AAS radio results in significant performance gains because of the higher degrees of freedom provided by the larger number of radio chains, also referred to as Massive MIMO.<br><br>**Beamforming**<br>When transmitting, beamforming is the ability to direct radio energy through the radio channel toward a specific receiver, as shown in the top left quadrant of **Figure 1**. By adjusting the phase and amplitude of the transmitted signals, constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput. Similarly, when receiving, beamforming is the ability to collect the signal energy from a specific transmitter. The beams formed by an AAS are constantly adapted to the surroundings to give high performance in both UL and DL.” |

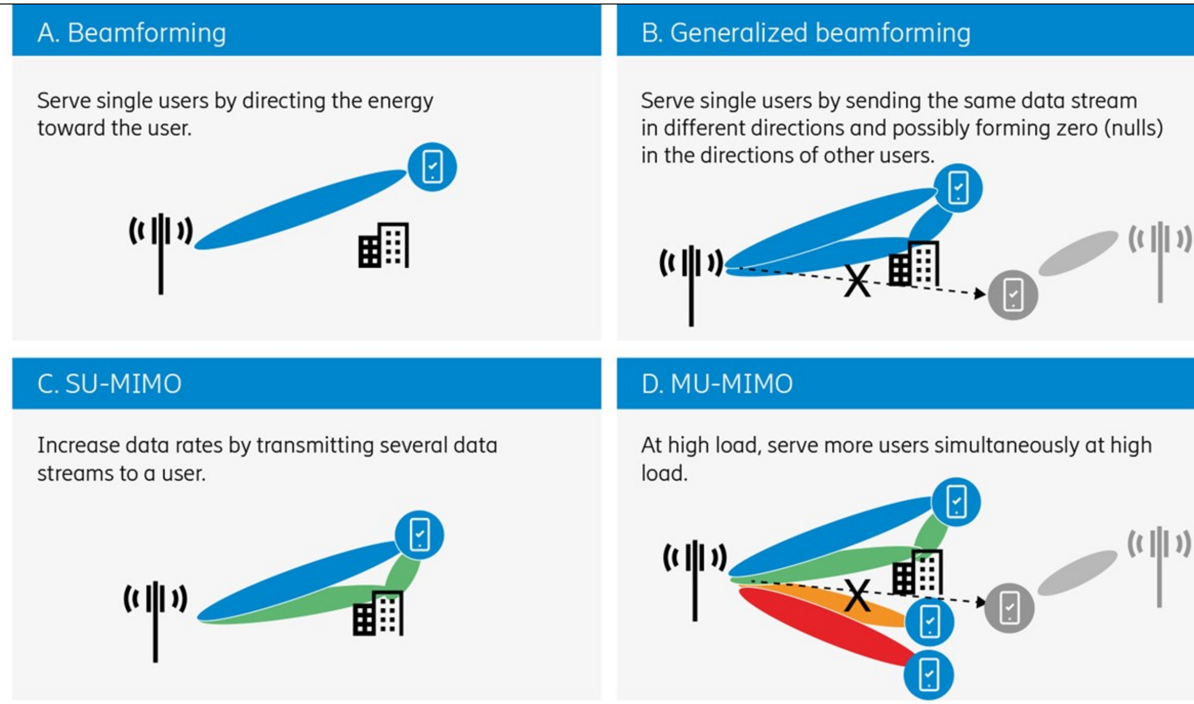


Figure 1: Beamforming and MIMO, with the different colors of the filled beams representing streams.

Although often very effective, transmitting energy in only one direction does not always provide an optimum solution. In multi-path scenarios, where the radio channel comprises multiple propagation paths from transmitter to receiver through diffraction around corners and reflections against buildings or other objects, it is beneficial to send the same data stream in several different paths (direction and/or polarization) with phases and amplitudes controlled in a way that they add constructively at the receiver [5]. This is referred to as generalized beamforming, as shown in the upper right quadrant of Figure 1. As part of generalized beamforming, it is also possible to reduce interference to other UEs, which is known as null forming. This is achieved by

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| | controlling the transmitted signals in a way that they cancel each other out at the interfered UEs.<br><br>**MIMO (Multiple Input, Multiple Output) techniques**<br>Spatial multiplexing, here referred to as MIMO, is the ability to transmit multiple data streams, using the same time and frequency resource, where each data stream can be beamformed. The purpose of MIMO is to increase throughput. MIMO builds on the basic principle that when the received signal quality is high, it is better to receive multiple streams of data with reduced power per stream, than one stream with full power. The potential is large when the received signal quality is high and the streams do not interfere with each other. The potential diminishes when the mutual interference between streams increases. MIMO works in both UL and DL, but for simplicity the description below will be based on the DL.<br><br>Single-user MIMO (SU-MIMO) is the ability to transmit one or multiple data streams, called layers, from one transmitting array to a single user. SU-MIMO can thereby increase the throughput for that user and increase the capacity of the network. The number of layers that can be supported, called the rank, depends on the radio channel. To distinguish between DL layers, a UE needs to have at least as many receiver antennas as there are layers.<br><br>SU-MIMO can be achieved by sending different layers on different polarizations in the same direction. SU-MIMO can also be achieved in a multi path environment, where there are many radio propagation paths of similar strength between the AAS and the UE, by sending different layers on different propagation paths, as shown in the bottom left quadrant of Figure 1.<br><br>In multi-user MIMO (MU-MIMO), which is shown in the bottom right quadrant of Figure 1, the AAS simultaneously sends different layers in separate beams to different users using the same time and frequency resource, thereby increasing the network capacity. In order to use MU-MIMO, the system needs to find two or more users that need to transmit or receive data at the very same time. Also, for efficient MU-MIMO, the |

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| | interference between the users should be kept low. This can be achieved by using generalized beamforming with null forming such that when a layer is sent to one user, nulls are formed in the directions of the other simultaneous users.<br><br>The achievable capacity gains from MU-MIMO depend on receiving each layer with good signal-to-interference-and-noise-ratio (SINR). As with SU-MIMO, the total DL power is shared between the different layers, and therefore the power (and thus SINR) for each user is reduced as the number of simultaneous MU-MIMO users increases. Also, as the number of users grows, the SINR will further deteriorate due to mutual interference between the users. Therefore, the network capacity typically improves as the number of MIMO layers increases, to a point at which power sharing and interference between users result in diminishing gains, and eventually also losses.<br><br>It should be noted that the practical benefits of many layers in MU-MIMO are limited by the fact that, in today's real networks, even with a high number of simultaneous connected users, there tends not to be many users who want to receive data simultaneously. This is due to the bursty (chatty) nature of data transmission to most users. Since the AAS and the transport network must be dimensioned for the maximum number of layers, the MNO needs to consider how many layers are required in their networks. In typical MBB deployments with the current 64T64R AAS variants, the vast majority of the DL and UL capacity gains can be achieved with up to 8 layers."<br><br>***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine |

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| | how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.<br><br>DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short- term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics.<br><br>The suitable channel knowledge scheme to use depends on UL coverage and UE capabilities. In cases where UL coverage is limiting, UE feedback offers a more robust |

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| | operation, whereas full UL channel estimation is applicable in scenarios with good coverage. In short, both reciprocity and UE feedback-based beamforming are needed.<br><br>**Antenna array structure**<br>The purpose of using a rectangular antenna array, as shown in section A of Figure 2, is to enable high-gain beams and make it possible to steer those beams over a range of angles. The gain is achieved, in both UL and DL, by constructively combining signals from a number of antenna elements. The more antenna elements there are, the higher the gain. Steerability is achieved by individually controlling the amplitude and phase of smaller parts of the antenna array. This is usually done by dividing the antenna array into so called sub-arrays (groups of non-overlapping elements), as shown in section C of Figure 2, and by applying two dedicated radio chains per sub-array (one per polarization) to enable control, as shown in section D. In this way it is possible to control the direction and other properties of the created antenna array beam. |

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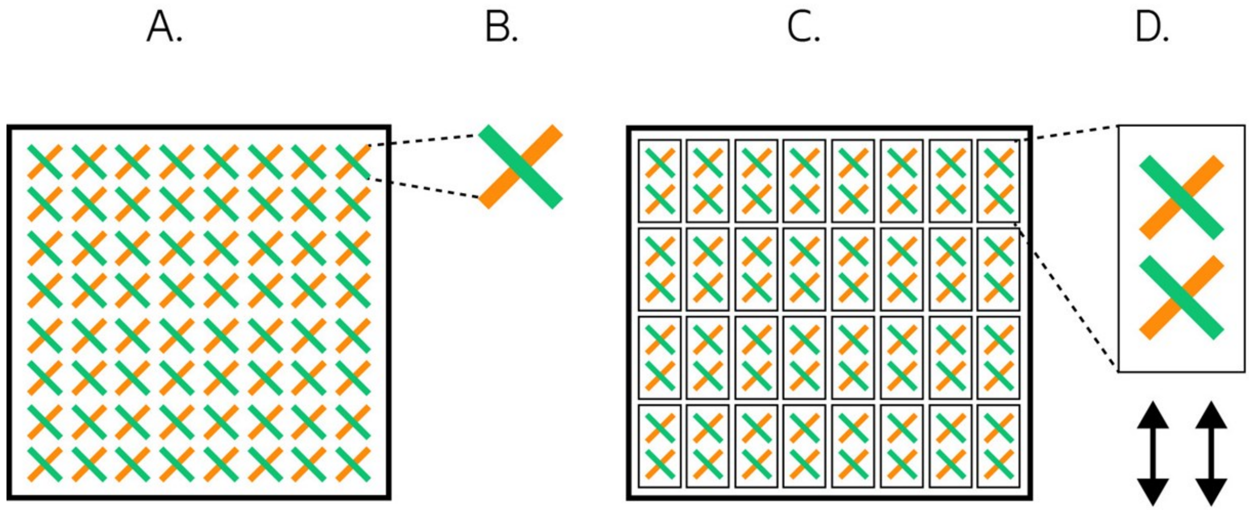
| | <br>Figure 2: A typical antenna array (A) is made up of rows and columns of individual dual-polarized antenna elements (B). Antenna arrays can be divided into sub-arrays (C), with each sub-array (D) connected to two radio chains, normally one per polarization.<br><br>To see how an antenna array creates steerable high-gain beams, we start with an antenna array of a specific size, which is then divided into sub-arrays of different sizes. For illustrative purposes, we describe only one dimension. The same principles do, however, apply to both vertical and horizontal dimensions.<br><br>The array gain is referred to as the gain achieved when all sub array signals are added constructively (in phase). The size of the array gain, relative to the gain of one sub-array, depends on the number of sub-arrays – for example, two sub-arrays gives |

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| | an array gain of 2 (i.e. 3 dB). By changing the phases of the sub-array signals in a certain way, this gain can be achieved in any direction, as shown in section A of Figure 3.<br><br>Each sub-array has a certain radiation pattern describing the gain in different directions. The gain and beam width depend on the size of the sub-array and the properties of the individual antenna elements. There is a trade-off between sub-array gain and beam width – the larger the sub-array, the higher the gain and the narrower the beam width, as illustrated in section B of Figure 3.<br><br>The total antenna gain is the product of the array gain and the sub-array gain, as shown in section C of Figure 3. The total number of elements determines the maximum gain and the sub-array partitioning allows steering of high gain beams over the range of angles. Moreover, the sub-array radiation pattern determines the envelope of the narrow beams (the dashed shape in section C of Figure 3). This has an implication on how to choose antenna array structure in a real deployment scenario with specific coverage requirements. Since each sub-array is normally connected to two radio chains and each radio chain is associated with a cost in terms of additional components, it is important to consider the performance benefits of additional steerability when choosing a cost-efficient array structure. |

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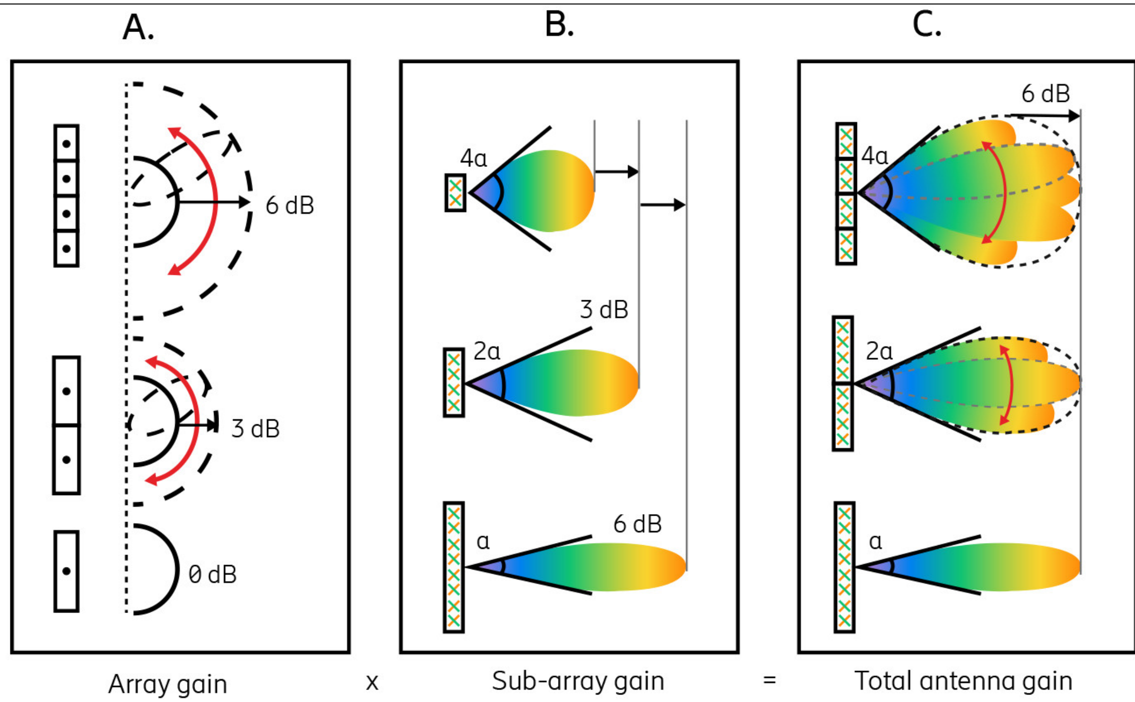
| |  <br><br>Figure 3: An array of sub-arrays supporting high total antenna gain and steerability.<br><br>**Deployment scenarios**<br>Determining what kind of AAS configuration is most appropriate and cost effective for a particular deployment scenario requires a mix of knowledge about the scenario, possible site constraints and available AAS features, particularly the need for vertical steerability of beams, the applicability of reciprocity-based beamforming and the gain from MU-MIMO. |

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| | **Deployment scenarios**<br>Determining what kind of Massive MIMO configuration is most appropriate and cost-effective for a particular deployment scenario requires a mix of knowledge about the scenario, possible site constraints, and available Massive MIMO features, particularly the need for vertical steerability of beams, the applicability of reciprocity-based beamforming and the gain from MU-MIMO. It should be noted that horizontal beamforming is a very effective feature that provides large gains in all scenarios since the users are generally spread in the horizontal dimension. Therefore, a large number of columns is beneficial in all scenarios.<br><br>We have chosen three typical use cases to illustrate different aspects of Massive MIMO deployment: rural/suburban, urban low-rise, and dense urban high-rise. More comprehensive and practically useful recommendations can be found in[3]. The scenarios, including relevant characteristics, suitable Massive MIMO configurations, and performance potential are depicted in Figure 4. More elaborate evaluations of the performance achievable with Massive MIMO are available in reference[2] and[3]. |

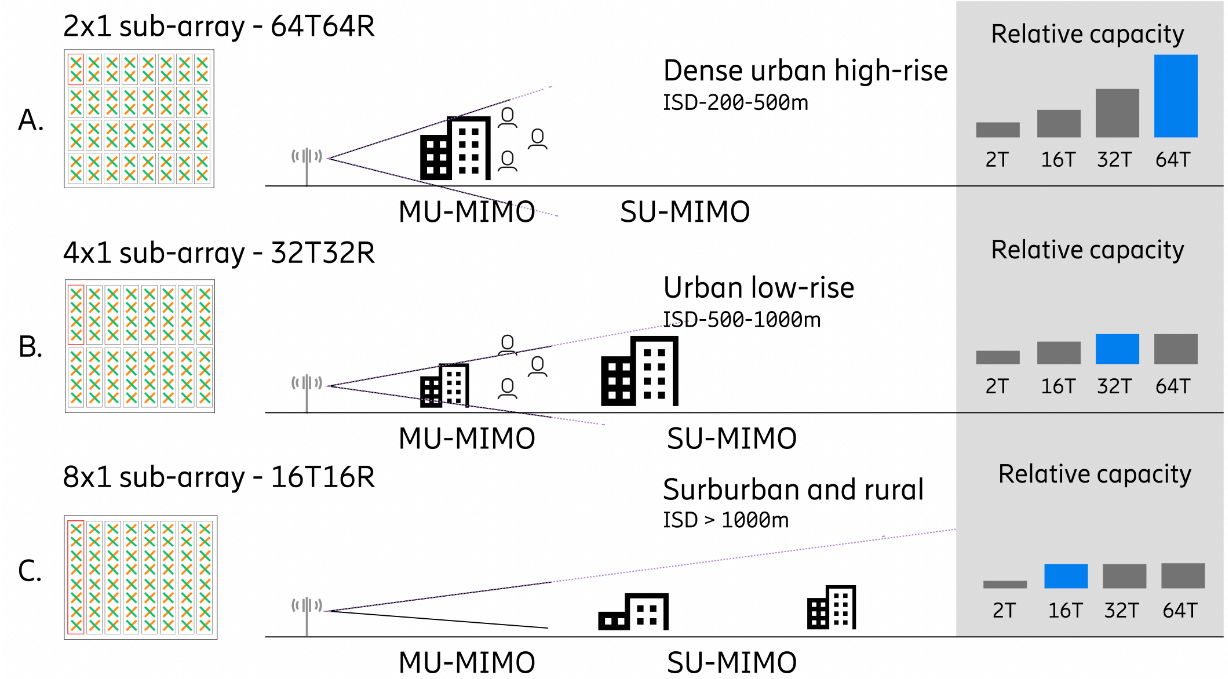


Figure 4: Suitable Massive MIMO configurations, schematic MU-MIMO and SU-MIMO usage ranges, and typical capacity gains in different deployment scenarios

***Deployment scenario #1: Dense urban high-rise***
As depicted in section A of Figure 4, the dense urban high-rise scenario is characterized by high-rise buildings, short inter-site-distances (ISDs) of 200-500m, large traffic volume, and high subscriber density with significant user spread in the vertical dimension. The main network evolution driver has increased capacity or equivalently high end-user throughput for a given traffic load.

For conventional non-beamformed systems such as 2T2R, the vertical spread of users in combination with the small ISD creates a situation where many users are outside the vertical main beam of the nearest base station. Together with the high site density,

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| | this leads to a situation where the signals from interfering base stations are strong, and severe interference problems may occur.<br><br>Desired Massive MIMO characteristics in the dense urban high-rise scenario include an antenna area large enough to ensure sufficient coverage (UL cell-edge data rate). Further, the vertical coverage range needs to be large enough to cover the vertical spread of users. This calls for small sub-arrays, which have a wide beam in the vertical direction. Partitioning the antenna into small vertical sub-arrays results in high-gain beams that can be steered over a large range of angles and effectively addresses the interference problems seen with conventional systems. The Massive MIMO radio needs to have a sufficient number of radio chains to support the relatively large number of sub-arrays. The good coverage and large spread of users mean that the potential for reciprocity-based beamforming and MU-MIMO with a relatively large number of multiplexed users is high, and the Massive MIMO radio should support these techniques. A good trade-off between complexity and performance could be achieved with 64 radio chains controlling small sub-arrays.<br><br>***Deployment scenario #2: Urban low-rise***<br>The urban low-rise scenario illustrated in section B of Figure 4 represents many of the larger cities around the world, including the outskirts of many high-rise cities. Base stations are typically deployed on rooftops, with inter-site distances of a few hundred meters. Compared to the dense urban high-rise scenario, traffic per area unit is lower. There is generally a mix of building types, which creates multipath propagation between the Massive MIMO radio and the UE. Maximizing the antenna area is important for improving the UL cell-edge data rates, especially for higher frequency bands employing TDD. Due to larger ISDs and decreased vertical spread of users (lower buildings), the vertical coverage range can be decreased compared to dense urban high-rises; hence, larger vertical sub-arrays can be used and there is less gain from vertical beamforming. Using larger sub-arrays for a given antenna area means that fewer radio chains are required. Reciprocity-based beamforming schemes will work for most users, but there will be users with poor coverage that need to rely on techniques such as feedback-based beamforming. MU-MIMO is also appropriate at |

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| | high loads due to the multi-path propagation environment, good link qualities, and UE pairing opportunities. A good trade-off between complexity and performance is a Massive MIMO radio with 16 to 32 radio chains.<br><br>***Deployment scenario #3: Rural/suburban***<br>Rural or suburban macro scenarios, as depicted in section C of Figure 4, are characterized by rooftop or tower-mounted base stations with inter-site distances ranging from one to several kilometers, low or medium population density and very small vertical user distribution. This scenario calls for a Massive MIMO radio with a large antenna area and the ability to support horizontal beamforming. Vertical beamforming, however, does not provide any significant gains as the vertical user spread is low. Therefore, large vertical sub-arrays with small vertical coverage areas are possible. Reciprocity-based beamforming is supported for a smaller fraction of users than in the other scenarios, and MU-MIMO gains are more limited. A good trade-off between complexity and performance is a Massive MIMO radio with 8 to 16 radio chains.<br><br>**Evolution of Massive MIMO**<br>The brief explanation of Massive MIMO above reflects the solutions in use to date (2022- Q4). The evolution of Massive MIMO is very rapid, and several tracks are being investigated to achieve higher performance. A few examples include the use of higher numbers of radio chains, larger array panels, the use of new and higher frequencies, and the use of multiple transmission points (multi-TRP). In addition to advancements in technologies specific to Massive MIMO, the use of interworking between Massive MIMO and conventional radios on other frequency bands add additional capacity beyond the sum of the two, respectively. Other developing technologies, e.g. artificial intelligence and machine learning (AI/ML) will also be applied in Massive MIMO to improve performance. Yet other technology developments, relating to for example energy performance, cost efficiency, and site deployment, are coming into use to make Massive MIMO a highly competitive and commercially viable option for mass deployment in a large variety of scenarios |

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| | For example, Ericsson published "How to build high-performing Massive MIMO systems," Billy Hogan, Bo Göransson, Sebastian Faxér, Sibel Tombaz, available athttps://www.ericsson.com/en/blog/2021/2/how-to-build-high-performing-massive-mimo-systems. This article explains that Massive MIMO solutions or advanced antenna systems (AAS) with beamforming features comprises an AAS radio and Massive MIMO features such as beamforming which can be executed by algorithms in the AAS radio or a RAN Compute connected to the AAS radio or both. It further describes the use of channel estimation to understand multipath transmission delay and reshape beams in both time and frequency to modify the transmission power level of multiple OFDM tones:<br><br>"Of course, just being able to focus energy in a fixed direction is not very useful as people typically move around. So, to be able to control the direction and shape of the beams in any way we want in space, we also make the antennas individually controllable with their own radio chains, so we can change the amplitude and phase of their signals separately.<br><br>This gives us numerous coverage and capacity abilities, including:<br><br>• To create multiple beams at the same time<br>• To send and receive radio signals extremely quickly – on a fraction of a millisecond basis – where we want to, while reducing interference in directions where we don´t want that energy to go or come from. All of this, for multiple users simultaneously!<br><br>But - this is no easy task. How do we "form" the right beams to get the most signal energy to the user that we want? People usually think of a beam as a simple concentration of energy that looks like the figure below. You just point it in the direction that you want and that´s all that you need. It is true that you can form beams like that, and they will often work quite well, but they are not always optimal.<br><br>The reason we can do better than a simple beam is that the "radio channel" is a highly complicated environment, since the signal path that travels between the base station and each device reflects off numerous objects causing standing waves and dips that |

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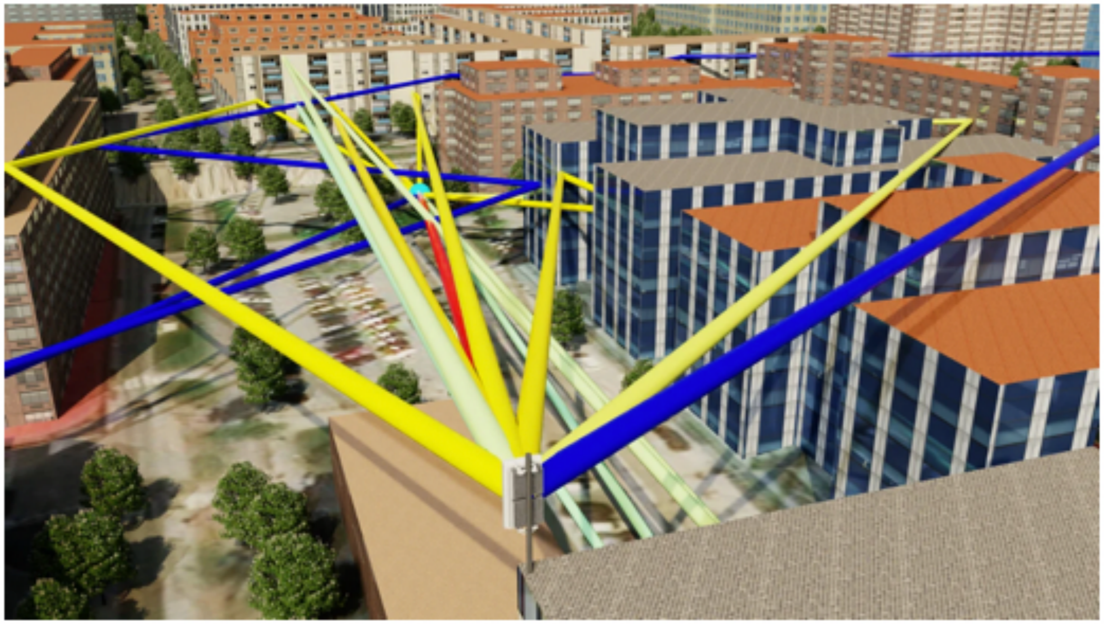
| | change in time and in frequency at sub millisecond level, as multiple paths arrive at the receiver from all directions, as illustrated in the picture below.  Think of a choppy ocean… what should the ideal beams look like to navigate this environment with the best performance? To add to the complexity, this channel is different for each of the hundreds of moving devices that are connected within a cell so they each need precisely created beams of their own and of course when we send a beam to one user we don't want to interfere with others. So, the beams must be highly precise, individual, and continually reshaped every fraction of a millisecond both in time and frequency, based on instant measurements of the radio channel across the spectrum together with large scale calculations to work out and apply the beams to the data we want to send or receive. The gigabits of data that are sent and received over the air interface are practically surfing the radio channel and just as in wave surfing, precise timing is essential to catch the radio waves. If you |

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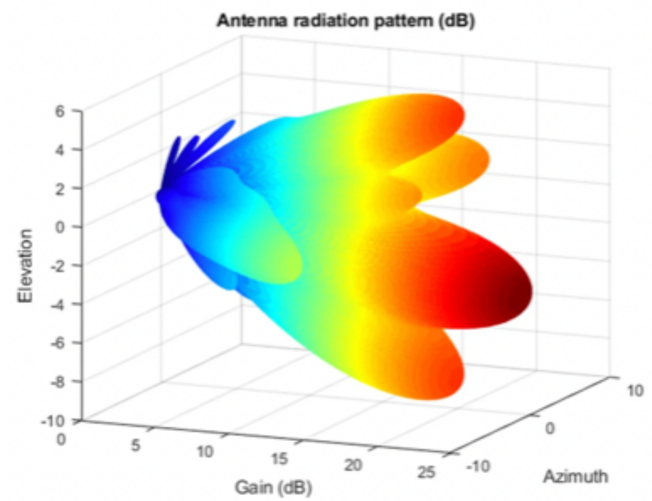
| | let your view of the channel information get too old, which happens extremely quickly, you will fall off the wave, and miss the chance to optimize your beamforming performance. The instantaneous beam that works best can look quite arbitrary as illustrated below but best achieves the goal of getting the energy exactly where we want until we change it for a new beam a fraction a millisecond later.<br><br><br>For CSPs, the result is much greater coverage, much greater network capacity and high end-user speeds over a wider area compared to remote radio unit solutions. The CSP can exploit their valuable spectrum resources to the utmost without vastly increasing the number of sites. This has the benefit of reducing the cost per gigabit per area while preparing CSPs for future traffic growth - they can continue providing outstanding speeds and great coverage as the data traffic load gets heavier.<br><br>**The art and science behind Ericsson Advanced Antenna Systems**<br>We can clearly see the benefits of AAS. However, there are also challenges to realize its full potential: |

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| | <ul><li>**Radio challenges:** Larger bandwidth and more antenna branches drive the need for increased processing capacity, which drives higher power consumption, size and weight at the base station.</li><li>**Beamforming challenges:**<ul><li>The radio environment changes on sub-millisecond timeframes as the smartphone moves. Adding to this complexity is of course the hundreds of other devices that connect within the cell.</li><li>The beams must be continually reshaped every fraction of a millisecond, based on instant snapshots of the channel, both in time and frequency.</li><li>To adapt the beams in a complex radio environment for many users simultaneously when using multiple antennas, requires millions of mathematical calculations per second</li></ul></li></ul><br>To address these challenges, Ericsson adds three key components: **access** to information about the instantaneous radio channel, clever **algorithms** which utilize this information, and the processing power of the Ericsson **silicon**. Fortunately, Ericsson's long experience in the AAS field has ensured that both our hardware design and beamforming algorithms are prepared for this.<br><br>The Ericsson Massive MIMO architecture has been designed to put as much as possible of the beamforming and MIMO processing in the AAS radio itself, close to the antennas and radio channel, where we have **access** to real-time and fine granular information about the radio channel. Therefore, Ericsson is able to do channel estimation and beamforming weight calculations that follow the extremely rapid changes that occur on the radio channel almost instantaneously. You could say that Ericsson Massive MIMO antennas have a fingertip feel of the radio channel and can react to the real-time channel situation with the best possible beams.<br><br>Putting this processing in the radio where it belongs also has other advantages. The fronthaul bit rate from the radio to the RAN Compute is reduced, thus saving costs, and the RAN Compute can concentrate on its own tasks,- for example to schedule users |

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| | over many cells, and to encode and decode the data bits on the user plane, which must be well protected before they are sent over the air.<br><br>Secondly, we need clever beamforming **algorithms** to act on the channel data. In fact, the way to do the beamforming in 5G is not defined by any 3GPP standard and is completely up to implementation, which means there is a lot of room for innovation and artistic freedom.<br><br>To solve the complex challenge of adapting to time-varying radio channel, we need to generate ultra-precise beamforming by applying different precoder weights to the antenna elements of our array so that after passing through the wireless channel to the target user, the signals from the multiple antennas add up coherently to boost the signal. This is analogous to creating a harmony in music by playing several tones on the piano at certain specific intervals so that when added up they form a pleasant-sounding chord.<br><br>But we simultaneously want to reduce interference to other users by having the signals from the different antenna elements add up destructively, akin to creating a dissonant-sounding chord in music by playing tones with other intervals (like a diminished fifth). The problem to generate optimal beamforming performance to achieve these goals simultaneously then becomes similar to composing a musical arrangement with complex harmonies and passages, while handling multiple instruments simultaneously, both an art and a science! And as we know, it takes both skill and dedication to become a Mozart as it does to master the art of Massive MIMO.<br><br>To generate ultra-precise beamforming, a massive set of complex calculations needs to be performed in real-time, scaling with the number of antennas, the bandwidth and number of users. This adds up to millions of mathematical calculations per second, which requires an extreme processing capability. In addition, it also requires our sophisticated software features and algorithms to make sure that we leverage that hardware in the best way. This can only be achieved with Ericsson **silicon,** system on a chip (SoC) solution, as outlined in the previous blog. It can not only handle all that |

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| | processing capacity inside the Massive MIMO radio, but also creates much tighter integration of components inside the radio. This way, we can build a high-performing radio without adding size, weight or energy consumption.<br><br>Ericsson's white paper further describes deployment scenarios of Ericsson 5G NR RAN Solutions. *See id. See also* Bo Göransson, Ph.D., Ericsson, 5G – The Multi Antenna Advantage (Oct. 6, 2016), at 15, 30-32, available at http://www.1com.net/wp-content/uploads/2018/05/5G-multi-antenna-advantage.pdf<br><br>See https://www.nokia.com/networks/mobile-networks/airscale-radio-access/active-antennas/:<br><br>The AirScale active antenna portfolio includes a full range of high-performance beamforming products ensuring the most space- and energy-efficient site solutions. The portfolio supports the numerous frequency bands in use around the World as well as fulfilling operators' unique and varied deployment needs.<br><br>**Massive MIMO Adaptive Antennas**<br><br>Our AirScale massive MIMO Adaptive Antennas portfolio includes 32TRX and 64TRX for the TDD 4G and 5G mid-bands and dual-band 16TRX for FDD bands. Each enabling the deployment of beamforming optimized solutions covering all deployment scenarios, from dense-urban capacity to wide-area coverage |

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| | **New generation Massive MIMO Adaptive Antennas**<br><br>Our AirScale massive MIMO Adaptive Antennas portfolio includes 32TRX and 64TRX for the TDD 4G and 5G mid-bands and dual-band 16TRX for FDD bands. These enable the deployment of beamforming optimized solutions covering all deployment scenarios, from dense-urban capacity to wide-area coverage.<br><br>Powered by Nokia new generation ReefShark System on Chip (SoC), these new generation massive MIMO antennas are light in weight and industry leading at 17 kilograms. This simplifies deployment considerations and eases installation, speeding-up the rollout of 5G.<br><br>These new designs also support high RF bandwidths, up to 400 MHz, making them ideal for covering fragmented spectrum or network sharing use cases. The ability to support high bandwidth can mean the difference between deploying one or multiple antennas.<br><br>Available in both 32TRX and 64TRX configurations, these industry leading antennas are the ideal choice for all 5G network deployments, delivering high-performance and high-efficiency, while also simplifying site solutions. |

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| | **New 32TRX massive MIMO antennas**<br>Industry leading solutions, supporting both 400 MHz RF bandwidth and the lightest weight, 17kg<br><br>**New 64TRX massive MIMO antennas**<br>400 MHz RF bandwidth and high power for maximum capacity and coverage<br><br>**Powered by new generation Nokia ReefShark SoCs**<br>The foundation for high RF bandwidth and high performance<br><br><br><br>See all additional evidence cited in charts above which is expressly incorporated by reference here. |

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| | See, e.g., 3GPP TS 38.214 v 16.2.0 R16 (2020-07) (incorporated by reference herein)<br><br>§ 5.2.2.2 Precoding matrix indicator (PMI)<br><br>[describing Type I and Type II and Enhanced Type II Codebooks for MIMO beamforming precoding matrix]<br>…<br>5.2.2.2.1 Type I Single-Panel Codebook<br>…<br>5.2.2.2.2 Type I Multi-Panel Codebook<br>…<br>5.2.2.2.3 Type II Codebook<br>…<br>5.2.2.2.4 Type II Port Selection Codebook<br>…<br>5.2.2.2.5 Enhanced Type II Codebook<br>…<br>5.2.2.2.6 Enhanced Type II Port Selection Codebook<br>…<br><br>See, e.g., Ziao Qin and Haifan Yin, A Review of Codebooks for CSI Feedback in 5G New Radio and Beyond, arXiv:2302.09222v2 13 Jun 2023 |

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| | [describing Type I and Type II and Enhanced Type II Codebooks for MIMO beamforming precoding matrix]<br><br>Multiple-Input Multiple-Output (MIMO) has been an integral technology to improve system performance since 4G LTE R8 released in 2009. In 5G NR, this technology has evolved to massive MIMO [2] with an increasing scale of the antenna array. Massive MIMO provides higher transmission diversity, higher spatial multiplexing gain, and higher transmission directivity. Hence, higher spectral efficiency and more reliability can be achieved [3]. Particularly, the key to high transmission directivity brought by massive MIMO is beamforming, which enables multi-user spatial multiplexing. To achieve accurate beamforming, Channel State information (CSI) is the indispensable premise. At the base station (BS) side, the downlink (DL) CSI can be acquired by the feedback information from the users (UEs), i.e., CSI report [4]. Note that CSI report is more indispensable in frequency division duplex (FDD) mode than time division duplex (TDD) mode [5]. The reported CSI enables the BS to calculate the precoding matrix for beamforming and user scheduling. In 3GPP standards, the CSI report process is achieved by the configuration of the codebook and the feedback of the codewords. At first, a codebook refers to a set of pre-defined precoders, a.k.a., codewords, and the UEs feed back the indices of the codewords to the base station. With the development of the standard nowadays, the meaning of codebook extends to the whole CSI report mechanism, which helps the base station compute the precoding matrix with the feedback from the UEs.<br><br>As another example, 5G NR beamforming technology is described in secondary sources, such as "MIMO Beamforming Using PMI Type II Precoding," Caroline Jenisha Ruth Mary Pramila Paul Sudhakar, Degree Project in Electrical Engineering, Second Cycle, Stockholm, Sweden 2021, KTH Royal Institute of Technology, available at https://www.diva-portal.org/smash/get/diva2:1618389/FULLTEXT01.pdf. This project lists Carolina Jenisha R P of KTH Royal Institute of Technology as Author with Ericsson AB as Host Company, Medhat |

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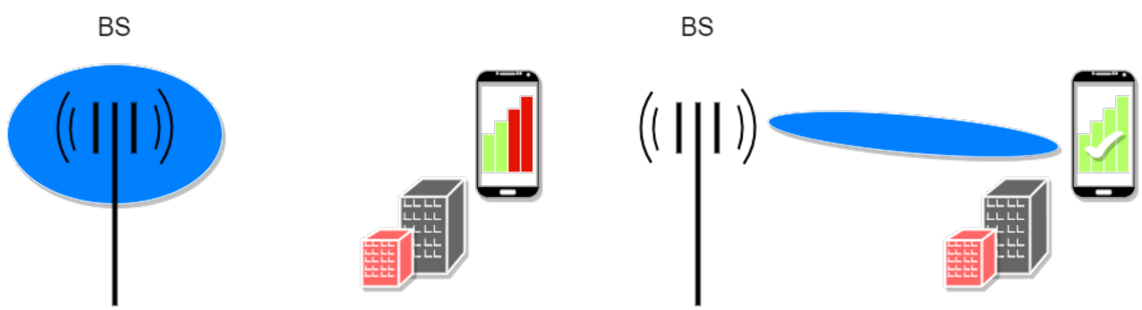
| | Mohammad of Ericsson AB as Supervisor, and Ben Slimane of KTH Royal Institute of Technology as Examiner.<br><br>**2.2.1 Beamforming**<br><br>Focusing the power of all antenna elements combined with the help of beamformers or weights towards one direction is called beamforming as shown in figure 2.2.1. When the angular spread between the BS and UE is zero (i.e.) in the existence LOS or one dominant path the above definition applies. In reality, there exists multiple paths (i.e.) NLOS or multiple paths, which requires *precoding* at the transmitter or receiver. Precoder applies weights on to the antenna element that comprises of amplitude and phase for each antenna element. With the help of weights, the antenna can be electronically steered to radiate in the intended direction by suppressing the power in the other directions. Beamformers can be precoded to radiate in two or more propagating path making use of the diversity gain provided by the fading channel. In general, BF can be considered as a special case of precoding for LOS path. The precoded data is spatially combined and transmitted.<br><br>When BF is implemented at the the receiver added to BF at the transmitter provides<br><br>CHAPTER2. THEORETICAL CONCEPTS AND RELATED WORK<br><br><br><br><br>Figure 2.2.1: Compared to the BS with isotropic radiation (left) and BS that performs beamforming (right), the signal strenght of beamformed signal increases directivity |

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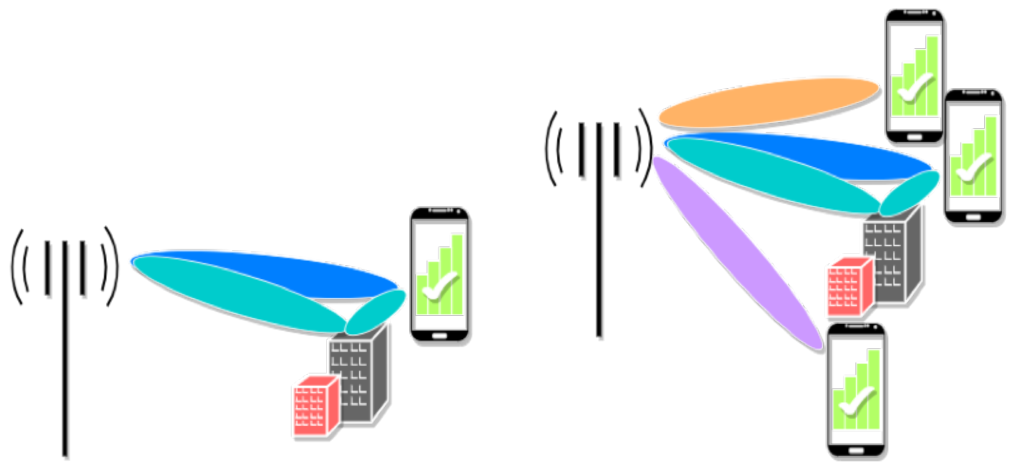
| | towards the user which increases the received power thereby increasing the links data rate.<br><br>both array gain and diversity gain. As the number of antenna elements increases at the receiver, increases the average Signal to Noise Ratio (SNR) achieved by coherently combining all the antenna elements on the other hand diversity gain helps to increase the instantaneous SNR at the receiver by selective coherent combining of different antenna elements experiencing different fading pushing the combined SNR more concentrated towards the average SNR [11].<br><br>**2.2.2 Spatial Multiplexing**<br><br>The procedure beamforming when applied to different data streams can be spatially multiplexed in one time and frequency resource. The multipaths provided by MIMO is essentially used to improve the data rate of the UE. This can be visualised in two different scenarios as shown in figure 2.2.2.<br><br><br><br>Figure 2.2.2: Spatial multiplexing seen in SUMIMO(left) and MUMIMO(right). |

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| | **2.3 CSI reporting**<br><br>The BS requires a pretext before transmitting data to the respective user. This pretext is referred to the information about channel observed from the direction of the user. CSI report is considered as a feedback from UE that carries the channel information which helps in designing the precoder or choosing the optimum precoder in case of codebook based precoding.<br><br>**2.3.1 Beam Management**<br><br>CSI acquisition is done in two stages. The first stage is Beam Management (BM) where the UE measures the Reference Signal Received Power (RSRP) of the set of analog beams transmitted by the BS and reports the beam ID of the best beam to the BS [9]. NR DL measurements for BM include Synchronization Signals (SS) bursts and Channel State InformationReference Signals (CSIRS) or NR Uplink (UL) measurements for BM include Sounding Reference Signals (SRS) as shown in figure 2.3.1. In BM based CSIRS, a set of analog beams is sent by BS to UE and the UE reports the CSI to the BS [8]. On the other hand, in BM based SRS, channel measurements are sent by the UE via a set of analog beams and received by BS. BS selects the best analog beams after measurements based on channel reciprocity where angle of arrival becomes the angle of departure of analog beams [8]. This holds, for instance, if the UE has the ability to transmit and receive with the same number of antennas as in Time Division Duplexing (TDD) [9]. However, UEs may use a different number of antennas for transmission and reception where channel reciprocity could not be met. Additionally, SRS based BM is more suitable for linear precoders as the precoder matrix requires detailed CSI whereas CSI-RS based BM is more suitable for GoB precoders. According to 5G standardization, BM in general consists of beam sweeping, beam measurement, beam determination, beam reporting , beam maintenance and beam recovery [8, 9]. These procedures are repeated to update the links periodically.<br><br>**2.3.2 PMI report** |

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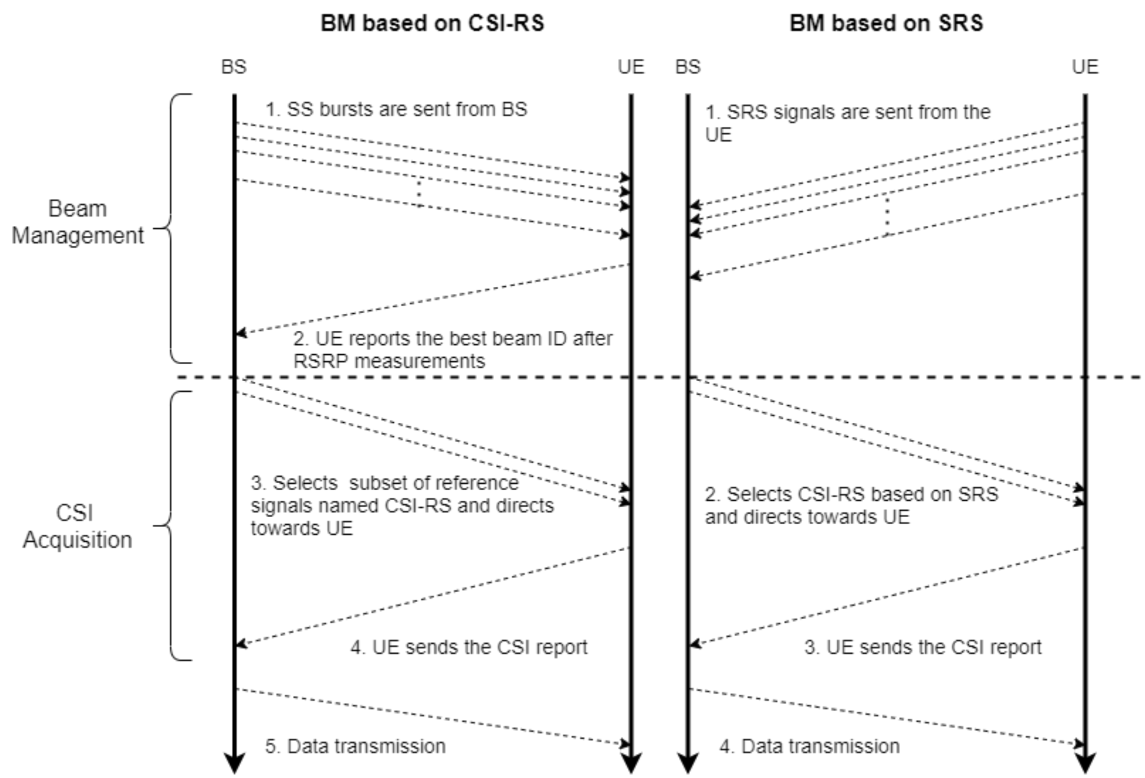
| | The first stage is followed by the second stage, namely CSI acquisition report from the UE. After the NR DL or UL BM measurements, the BS assigns a subset of analog beams towards that UEs location and the UE generates the CSI report and sends the report to the BS [8]. The CSI report contains,<br><br><br>Figure 2.3.1: Beam Management procedures<br>• *Rank Indicator (RI)*, used to indicate the preferred number of transmission layers. |

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| | • *Precoder Matrix Indicator (PMI)*, used to indicate preferred design of precoder matrix for the given rank.<br><br>• *Channel Quality Indicator (CQI)*, used to indicate the suitable channelcoding rate and modulation scheme for the given PMI. [2].<br><br>The PMI values corresponding to the different precoder matrix is chosen from the precoder codebook defined by the standards . Despite the CSI report sent by the UE, the network can choose any precoder matrix design for data transmission. Although choosing the precoder design preferred by UE makes sense, in many cases that is not entirely possible especially in MUMIMO [10]. Therefore, NR defines two different types of CSI that differ in size and structure of the precoder matrix. *Type I CSI* (standard/low resolution) is predominantly used for SUMIMO scenarios as it relies on the UE to suppress the interference due to the different layers. This is due to the fact that the number of layers will never be larger than the number of receiver antennas. On the other hand, *Type II CSI* (high resolution) is primarily used for MUMIMO and is limited to a smaller number of layers (maximum of two). Since the number of received streams is larger than the number of receiver antennas, the interference is managed by the BS with the help of BF or precoder design [9].<br><br>See also "Chapter 3: Methodologies," which is incorporated by reference herein.<br><br>5G NR beamforming is also described in secondary sources, such as Ziao Qin and Haifan Yin, "A Review of Codebooks for CSI Feedback in 5G New Radio and Beyond," submitted, February 2023, 10.48550/arXiv.2302.09222, available online: https://arxiv.org/abs/2302.09222, also available at https://www.researchgate.net/publication/368665066_A_Review_of_Codebooks_for_CSI_Feedback_in_5G_New_Radio_and_Beyond<br><br>5G NR beamforming is also described in secondary sources, such as on the NR Cell Performance Evaluation with MIMO page on https://www.mathworks.com/help/5g/ug/nr-cell-performance-evaluation-with-mimo.html. This explains that: |

# NR Cell Performance Evaluation with MIMO

This example models a 5G New Radio (NR) cell with multiple-input multiple-output (MIMO) antenna configuration and evaluates the network performance. You can customize the scheduling strategy to leverage the MIMO capabilities and analyze the performance. This example performs downlink (DL) and uplink (UL) channel measurements using multi-port channel state information reference signals (CSI-RS) and sounding reference signals (SRS), respectively. The gNB uses the measured channel characteristics to make MIMO scheduling decisions.

## Introduction

MIMO improves network performance by improving the cell throughput and reliability. The example performs layer mapping and precoding to utilize MIMO in the DL and UL directions.

This example models:

- Single-codeword DL spatial multiplexing to perform multi-layer transmission. Single-codeword limits the number of transmission layers to 4.
- Single-codeword UL spatial multiplexing. The 3GPP specification allows only single-codeword in UL direction which limits the number of transmission layers to 4.
- Precoding to map the transmission layers to antenna ports. The example assumes one-to-one mapping from antenna ports to physical antennas.
- DL channel quality measurement by UEs based on the multi-port CSI-RS received from the gNB. The same CSI-RS configuration applies to all the UEs.
- UL channel quality measurement by gNB based on the multi-port SRS received from the UEs. The example does not support UL rank estimation and provides the rank to be used for estimating UL precoding matrix as a configuration parameter.
- DL rank indicator (RI), precoding matrix indicator (PMI), and channel quality indicator (CQI) reporting by UEs. The example supports Type-1 single-panel codebook for PMI.
- Free space path loss (FSPL), additive white Gaussian noise (AWGN), and clustered delay line (CDL) propagation channel model.

Nodes send the control packets (buffer status report (BSR), DL assignment, UL grants, PDSCH feedback, and CSI report) out of band, without the need of resources for transmission and assured error-free reception.

## MIMO

The key aspects of MIMO include spatial multiplexing, precoding, channel measurement and reporting.

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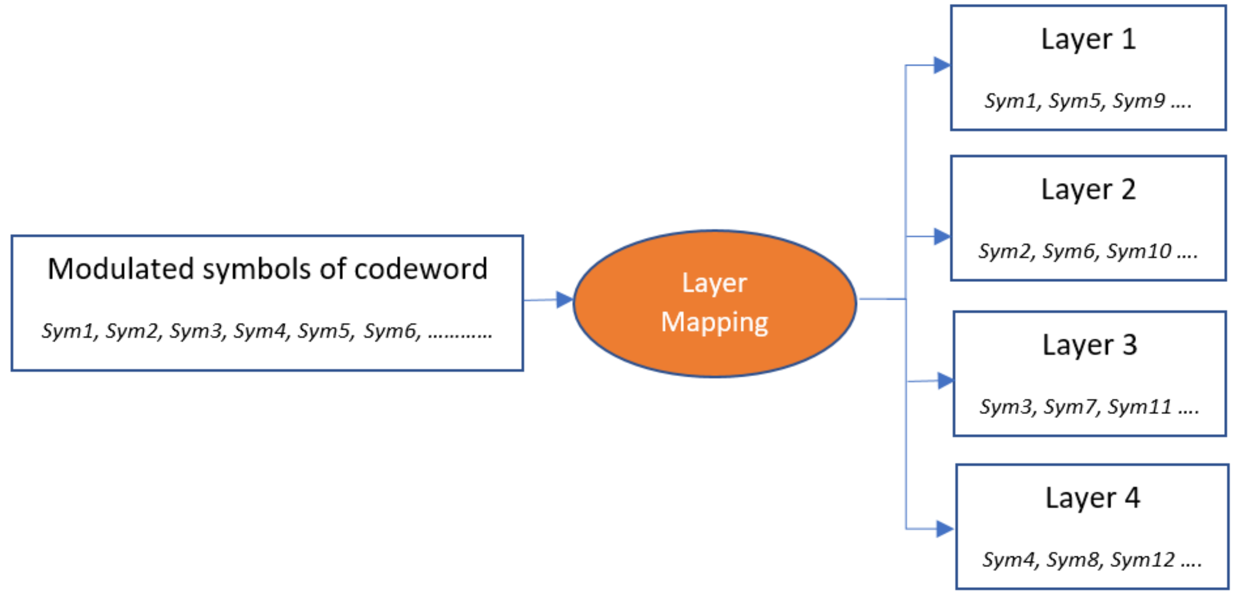
| | *Spatial multiplexing*<br><br><br>Spatial multiplexing utilizes MIMO to perform multi-layer transmission. The minimum of number of transmit and receive antennas limits the number of layers (or maximum rank). The layer mapping process maps the modulated symbols of the codeword onto different layers. It maps every $n_{\mathrm{th}}$ symbol of the codeword to $n_{\mathrm{th}}$ layer. For instance, this figure shows the mapping of a codeword onto four layers. Furthermore, in the DL direction, NR specification also allows two codewords and up to a maximum of 8 transmission layers. The example currently only supports single codeword for both DL and UL.<br>*Precoding* |

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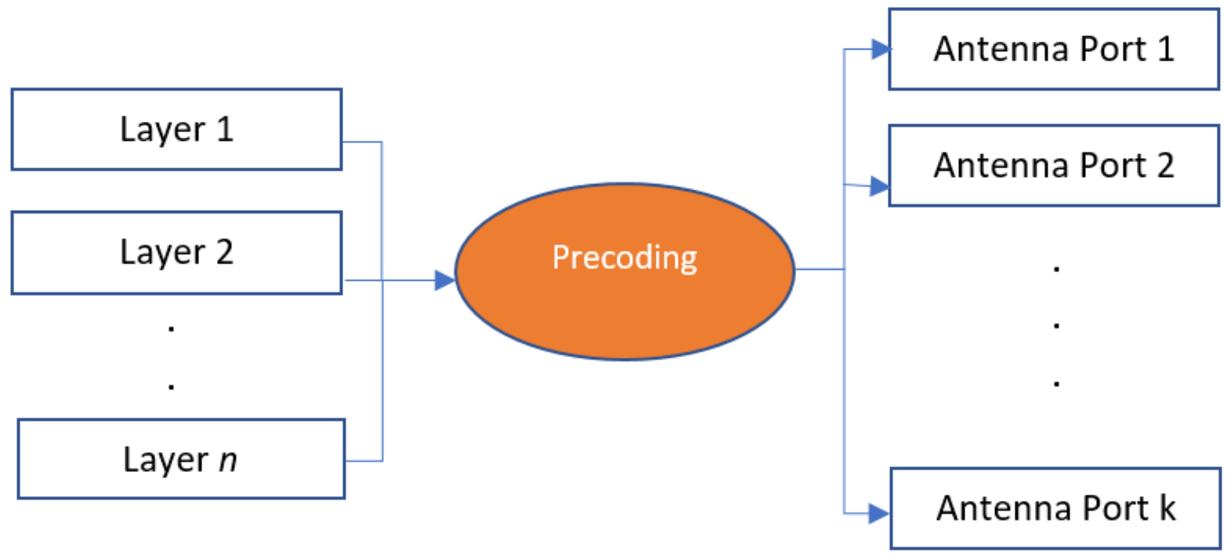
| | <br>Precoding, which follows the layer mapping, maps the transmission layers to antenna ports. Precoding applies a precoding matrix to the transmission layers and outputs data streams to the antenna ports.<br>*Channel measurement and reporting*<br>It consists of DL channel measurement and reporting by the UEs and UL channel measurement by gNB. |

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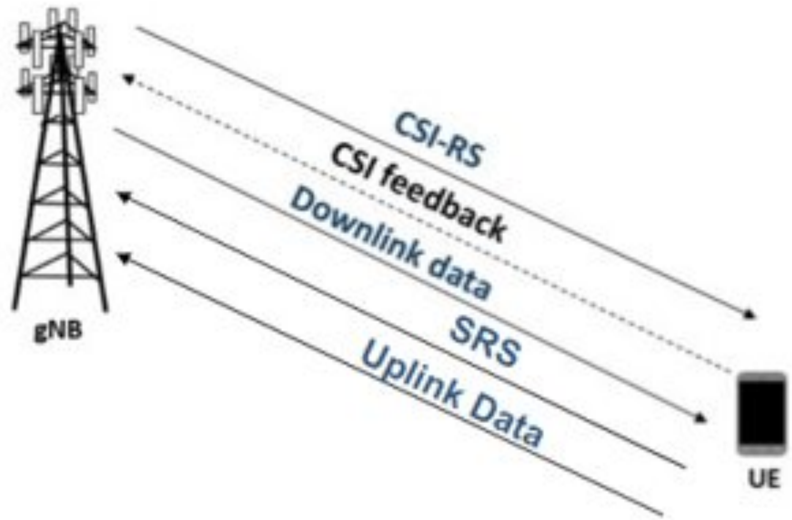
| | <br>*DL channel measurement and reporting*<br>CSI reporting is the process by which a UE, for DL transmissions, advises a suitable number of transmission layers (rank), PMI, and CQI values to the gNB. The UE estimates these values by performing channel measurements on its configured CSI-RS resources. For more details, see the 5G NR Downlink CSI Reporting example. The gNB scheduler uses this advice to decide the number of transmission layers, precoding matrix, and modulation and coding scheme (MCS) for PDSCHs.<br>*UL channel measurement*<br>gNB uses SRS to measure UL channel characteristics in a way analogous to CSI-RS based DL channel measurements. The UL channel measurements serve as an important input to the scheduler to decide the number of transmission layers, precoding matrix and MCS for PUSCHs.<br>[See additional excerpts reproduced in claim element 1[b] above].<br>Claim limitation 1[c] is literally infringed by each Accused Product. However, to the extent claim limitation 1[c] is not met literally, it is nonetheless met under the doctrine of equivalents because the differences between the claim limitation and each Accused Product would be |

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| | insubstantial, and each Accused Product performs substantially the same function, in substantially the same way, to achieve the same result as the claimed invention. For example, precoding coefficients / weights in the accused products performs substantially the same function of selectively setting different transmission power levels for at least two OFDM tones in substantially the same way of the precoding weights described above that are complex numbers whose amplitude determines the amount of power applied to the tones to achieve substantially the same result of pre-equalization based on the identified multipath transmission delay. *See* evidence cited in charts above.<br><br>Moreover, as noted above, the doctrine of equivalents theories for 1[a] and 1[b] above are expressly incorporated herein and apply to the same claim terms that also appear in 1[c]. |

# Claim 2

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| 2. The method as recited in claim 1, further comprising: receiving said reverse path data signal over at least one reverse transmission path. | The Accused Products/Instrumentalities perform the method as recited in claim 1, further comprising: receiving said reverse path data signal over at least one reverse transmission path. As described for claim 1, the examples of reverse path data signals are received over at least one reverse transmission path. Each reverse path data signal charted above is received by the Ericsson or Nokia base station over at least one reverse transmission path from the user equipment. The 3GPP 5G Technical Specifications, including those referenced in the charts above, and the other documentation referenced in the charts above, illustrates this. See claim 1 and evidence therein.<br><br>For example, the Sounding Reference Signal (SRS) is received from a user equipment over at least one reverse transmission path. For example, the user equipment transmits the SRS on at least one UE antenna port. This illustrates that there is at least one reverse transmission path for the SRS.<br><br>https://www.techplayon.com/nr-sound-reference-signal-nr-srs/<br><br>5G NR Sounding Reference Signal (NR-SRS)<br><br>In NR there are two types of Reference Signal in UL which gives information about the channel quality.<br><br>1. DMRS:- Demodulation Reference Signal<br>2. SRS:- Sounding Reference Signal<br><br>With the help of above two RS, gNB takes smart decisions for resource allocation for uplink transmission, link adaptation and to decode transmitted data from UE. SRS is a UL reference signal which is transmitted by UE to Base station. SRS gives information about the combined effect of multipath fading, scattering, Doppler and power loss of transmitted signal.<br><br>Hence Base Station estimates the channel quality using this reference signal and manages further resource scheduling, Beam management, and power control of signal. So SRS provides information to gNB about the channel over full bandwidth and using this information gNB takes decision for resource allocation which has better channel quality comparing to other Bandwidth regions.<br><br>One reference signal(DMRS) is always associated with each channel (PUCCH/PUSCH), which provides information about the radio channel then question may arise that why SRS is required? and here is the answer. |

1. DMRS provides information about the frequency region which is being used by PUSCH/PUCCH specifically.
2. If gNB assigns resources over full bandwidth region for a UE then there is no choice left for UE to select specific frequency region Hence SRS is optional. BUT DMRS will always be transmitted with PUSCH/PUCCH for coherent demodulation and channel estimation.

See 3GPP TS 38.211 version 15.8.0

### 6.4.1.4 Sounding reference signal

#### 6.4.1.4.1 SRS resource

An SRS resource is configured by the *SRS-Resource* IE and consists of

- $N_{\mathrm{ap}}^{\mathrm{SRS}} \in \{1,2,4\}$ antenna ports $\{p_i\}_{i=0}^{N_{\mathrm{ap}}^{\mathrm{SRS}}-1}$, where the number of antenna ports is given by the higher layer parameter *nrofSRS-Ports*, $p_i = 1000 + i$ when the SRS resource is in a SRS resource set with higher-layer parameter *usage* in *SRS-ResourceSet* not set to 'nonCodebook', or determined according to [6, TS 38.214] when the SRS resource is in a SRS resource set with higher-layer parameter *usage* in *SRS-ResourceSet* set to 'nonCodebook'
- $N_{\mathrm{symb}}^{\mathrm{SRS}} \in \{1,2,4\}$ consecutive OFDM symbols given by the field *nrofSymbols* contained in the higher layer parameter *resourceMapping*
- $l_0$, the starting position in the time domain given by $l_0 = N_{\mathrm{symb}}^{\mathrm{slot}} - 1 - l_{\mathrm{offset}}$ where the offset $l_{\mathrm{offset}} \in \{0,1,\ldots,5\}$ counts symbols backwards from the end of the slot and is given by the field *startPosition* contained in the higher layer parameter *resourceMapping* and $l_{\mathrm{offset}} \geq N_{\mathrm{symb}}^{\mathrm{SRS}} - 1$
- $k_0$, the frequency-domain starting position of the sounding reference signal

### 6.4.1.4.3 Mapping to physical resources

When SRS is transmitted on a given SRS resource, the sequence $r^{(p_i)}(n,l')$ for each OFDM symbol $l'$ and for each of the antenna ports of the SRS resource shall be multiplied with the amplitude scaling factor $\beta_{\mathrm{SRS}}$ in order to conform to the transmit power specified in [5, 38.213] and mapped in sequence starting with $r^{(p_i)}(0,l')$ to resource elements $(k,l)$ in a slot for each of the antenna ports $p_i$ according to

$$a^{(p_i)}_{K_{\mathrm{TC}}k'+k_0^{(p_i)},l'+l_0} = \begin{cases} \frac{1}{\sqrt{N_{\mathrm{ap}}}}\beta_{\mathrm{SRS}}r^{(p_i)}(k',l') & k'=0,1,\ldots,M^{\mathrm{SRS}}_{\mathrm{sc},b}-1 \quad l'=0,1,\ldots,N^{\mathrm{SRS}}_{\mathrm{symb}}-1 \\ 0 & \text{otherwise} \end{cases}$$

The length of the sounding reference signal sequence is given by

$$M^{\mathrm{SRS}}_{\mathrm{sc},b} = m_{\mathrm{SRS},b}N^{\mathrm{RB}}_{\mathrm{sc}}/K_{\mathrm{TC}}$$

where $m_{\mathrm{SRS},b}$ is given by a selected row of Table 6.4.1.4.3-1 with $b=B_{\mathrm{SRS}}$ where $B_{\mathrm{SRS}}\in\{0,1,2,3\}$ is given by the field *b-SRS* contained in the higher-layer parameter *freqHopping*. The row of the table is selected according to the index $C_{\mathrm{SRS}}\in\{0,1,\ldots,63\}$ given by the field *c*-SRS contained in the higher-layer parameter *freqHopping*.

## Claim 3

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| 3. The method as recited in claim 2, further comprising: transmitting said modified forward path data signal over at least one forward transmission path. | The Accused Products/Instrumentalities perform the method as recited in claim 2, further comprising: transmitting said modified forward path data signal over at least one forward transmission path. As described for claim 1, the pre-equalization parameters modify the forward path data signal that is transmitted over at least one forward transmission path in the downlink to the user equipment. The 3GPP 5G Technical Specifications, including those referenced in the charts above, and the other documentation referenced in the charts above, illustrates this. See claim 1 and evidence therein.<br><br>For example, the base station modifies subsequent downlink transmissions using a precoder and transmits the modified downlink transmission signal via antenna port(s), which illustrates that there is a forward transmission path.<br><br>See, e.g., Ericsson Advanced Antenna System for 5G Networks white paper / https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks (describing computing beamforming coefficients based on channel estimation over at least one forward transmission path toward the user equipment)<br><br>See https://www.sharetechnote.com/html/5G/5G_CSI_RS_Codebook.html:<br><br>**What is Codebook ?**<br><br>What is Codebook ? It would many different things in different situation, but the meaning of Codebook under the context of CSI-RS is a set of Precoders (a set of Precoding Matrix). Putting it other way, Codebook is a kind of matrix (a matrix having complex value elements) that transform the data bit (PDSCH) to another set of data that maps to each antenna port.<br>… |

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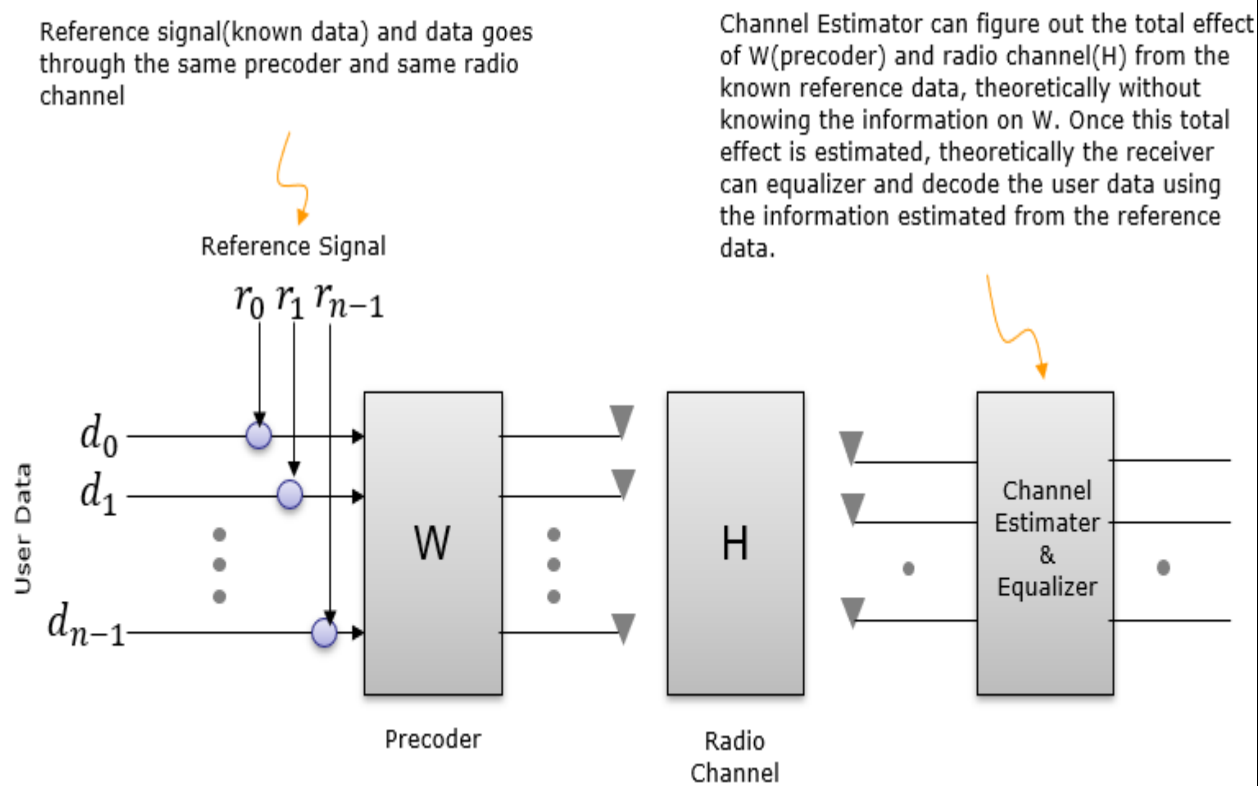
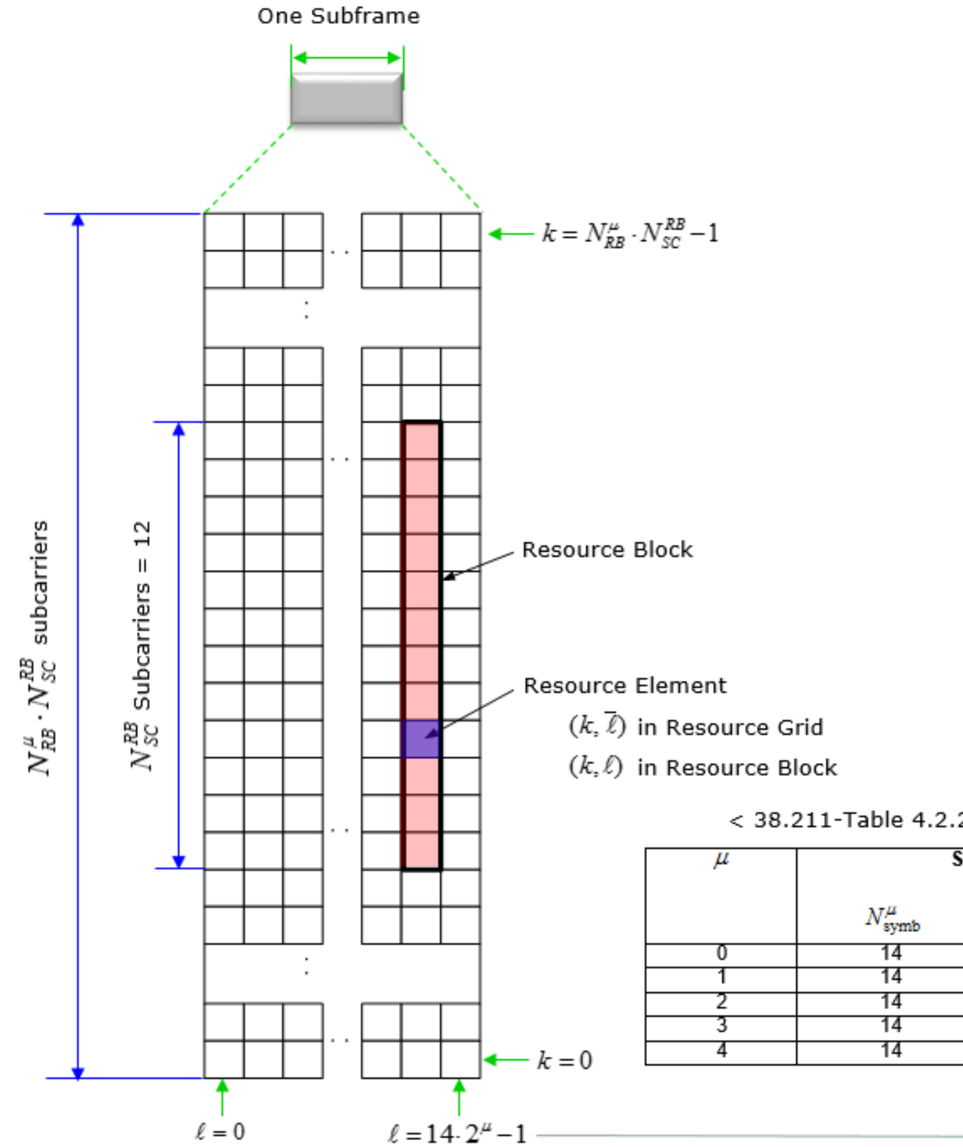
| | <br>See https://www.sharetechnote.com/html/5G/5G_ResourceGrid.html:<br>**Resource Grid**<br>The resource grid for NR is defined as follows. If you just take a look at the picture, you would think it is almost identical to LTE resource grid. But the physical dimension (i.e., subcarrier spacing, number of OFDM symbols within a radio frame) varies in NR depending on numerology. |




< 38.211-Table 4.2.2-1 >

| $\mu$ | Slot configuration 0 | | |
|---|---|---|---|
| | $N_{\mathrm{symb}}^{\mu}$ | $N_{\mathrm{frame}}^{\mathrm{slots},\mu}$ | $\ell = 14 \cdot 2^{\mu}$ - |
| 0 | 14 | 10 | 13 |
| 1 | 14 | 20 | 27 |
| 2 | 14 | 40 | 55 |
| 3 | 14 | 80 | 111 |
| 4 | 14 | 160 | 223 |

**Resource Element** : This is same as LTE. It is the smallest unit of the resource grid made up of one subcarrier in frequency domain and one OFDM symbol in time domain.

**Resource Block**: In NR, Resource Block is defined only for frequency domain. 38.211-4.4.4.1 states *'A resource block is defined as 12(N_RB_sc) consecutive subcarriers in the frequency domain'*.
Time domain definition of resource block is a little bit ambiguous. Minimum time domain length in a resource block can be one OFDM symbol, but exact time domain length vary depending SLIV.

**Resource Grid and Antenna port and Numerology** : Basically one resource grid is created for one antenna port and numerology. 38.211-4.2.2 states as follows.

- *There is one set of resource grids per transmission direction (uplink or downlink) with the subscript set to DL and UL for downlink and uplink*
- *There is one resource grid for a given antenna port p , subcarrier spacing configuration u, and transmission direction (downlink or uplink).*

The maximum and minimum number of Resource blocks for downlink and uplink is defined as below (this is different from LTE)

< 38.211 Table 4.4.2-1: Minimum and maximum number of resource blocks.>

| $\mu$ | $N^{\min,\mu}_{\mathrm{RB,DL}}$ | $N^{\max,\mu}_{\mathrm{RB,DL}}$ | $N^{\min,\mu}_{\mathrm{RB,UL}}$ | $N^{\max,\mu}_{\mathrm{RB,UL}}$ |
|---|---|---|---|---|
| 0 | 24 | 275 | 24 | 275 |
| 1 | 24 | 275 | 24 | 275 |
| 2 | 24 | 275 | 24 | 275 |
| 3 | 24 | 275 | 24 | 275 |
| 4 | 24 | 138 | 24 | 138 |

See, e.g., 3GPP TS 38.211 version 15.8.0

## 4.4 Physical resources

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| | **4.4.1 Antenna ports**<br><br>An antenna port is defined such that the channel over which a symbol on the antenna port is conveyed can be inferred from the channel over which another symbol on the same antenna port is conveyed.<br><br>For DM-RS associated with a PDSCH, the channel over which a PDSCH symbol on one antenna port is conveyed can be inferred from the channel over which a DM-RS symbol on the same antenna port is conveyed only if the two symbols are within the same resource as the scheduled PDSCH, in the same slot, and in the same PRG as described in clause 5.1.2.3 of [6, TS 38.214].<br><br>For DM-RS associated with a PDCCH, the channel over which a PDCCH symbol on one antenna port is conveyed can be inferred from the channel over which a DM-RS symbol on the same antenna port is conveyed only if the two symbols are within resources for which the UE may assume the same precoding being used as described in clause 7.3.2.2.<br><br>For DM-RS associated with a PBCH, the channel over which a PBCH symbol on one antenna port is conveyed can be inferred from the channel over which a DM-RS symbol on the same antenna port is conveyed only if the two symbols are within a SS/PBCH block transmitted within the same slot, and with the same block index according to clause 7.4.3.1.<br><br>Two antenna ports are said to be quasi co-located if the large-scale properties of the channel over which a symbol on one antenna port is conveyed can be inferred from the channel over which a symbol on the other antenna port is conveyed. The large-scale properties include one or more of delay spread, Doppler spread, Doppler shift, average gain, average delay, and spatial Rx parameters. |

## Claim 4

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| 4. The method as recited in claim 1, wherein said reverse path data signal includes at least one type of data selected from a group of different types of data comprising Orthogonal Frequency Division Multiplexing (OFDM) data and Quadrature Phase Shift Keying (QPSK) data. | The Accused Products/Instrumentalities perform the method as recited in claim 1, wherein said reverse path data signal includes at least one type of data selected from a group of different types of data comprising Orthogonal Frequency Division Multiplexing (OFDM) data and Quadrature Phase Shift Keying (QPSK) data. For example, the exemplary reverse path data signals includes at least OFDM data in 5G communications. See claim 1 and evidence therein.<br><br>For example, the UE transmission of the SRS or CSI includes OFDM data and QPSK symbols on subcarriers of the OFDM multiple access system.<br><br>See, e.g., 3GPP TS 38.211 version 15.8.0:<br><br>**5.3.1 OFDM baseband signal generation for all channels except PRACH**<br><br>The time-continuous signal $s_l^{(p,\mu)}(t)$ on antenna port $p$ and subcarrier spacing configuration $\mu$ for OFDM symbol $l \in \{0,1,\ldots,N_{\mathrm{slot}}^{\mathrm{subframe},\mu} N_{\mathrm{symb}}^{\mathrm{slot}} - 1\}$ in a subframe for any physical channel or signal except PRACH is defined by<br><br>$s_l^{(p,\mu)}(t) = \sum_{k=0}^{N_{\mathrm{grid}}^{\mathrm{size},\mu} N_{\mathrm{sc}}^{\mathrm{RB}} - 1} a_{k,l}^{(p,\mu)} \cdot e^{j2\pi\left(k + k_0^\mu - N_{\mathrm{grid},x}^{\mathrm{size},\mu} N_{\mathrm{sc}}^{\mathrm{RB}}/2\right)\Delta f\left(t - N_{\mathrm{CP},l}^\mu T_{\mathrm{c}} - t_{\mathrm{start},l}^\mu\right)}$<br><br>$k_0^\mu = \left(N_{\mathrm{grid},x}^{\mathrm{start},\mu} + N_{\mathrm{grid},x}^{\mathrm{size},\mu}/2\right) N_{\mathrm{sc}}^{\mathrm{RB}} - \left(N_{\mathrm{grid},x}^{\mathrm{start},\mu_0} + N_{\mathrm{grid},x}^{\mathrm{size},\mu_0}/2\right) N_{\mathrm{sc}}^{\mathrm{RB}} 2^{\mu_0 - \mu}$<br><br>where $t_{\mathrm{start},l}^\mu \le t < t_{\mathrm{start},l}^\mu + \left(N_{\mathrm{u}}^\mu + N_{\mathrm{CP},l}^\mu\right) T_{\mathrm{c}}$ is the time within the subframe,<br><br>$N_{\mathrm{u}}^\mu = 2048\kappa \cdot 2^{-\mu}$<br><br>$N_{\mathrm{CP},l}^\mu = \begin{cases} 512\kappa \cdot 2^{-\mu} & \text{extended cyclic prefix} \\ 144\kappa \cdot 2^{-\mu} + 16\kappa & \text{normal cyclic prefix, } l = 0 \text{ or } l = 7 \cdot 2^\mu \\ 144\kappa \cdot 2^{-\mu} & \text{normal cyclic prefix, } l \ne 0 \text{ and } l \ne 7 \cdot 2^\mu \end{cases}$<br><br>and<br><br>- $\Delta f$ is given by clause 4.2; |

## 5.1 Modulation mapper

The modulation mapper takes binary digits, 0 or 1, as input and produces complex-valued modulation symbols as output.

### 5.1.1 π/2-BPSK

In case of $\pi/2$-BPSK modulation, bit $b(i)$ is mapped to complex-valued modulation symbol $d(i)$ according to

$$d(i) = \frac{e^{j\frac{\pi}{2}(i \bmod 2)}}{\sqrt{2}}\left[(1-2b(i)) + j(1-2b(i))\right]$$

### 5.1.2 BPSK

In case of BPSK modulation, bit $b(i)$ is mapped to complex-valued modulation symbol $d(i)$ according to

$$d(i) = \frac{1}{\sqrt{2}}\left[(1-2b(i)) + j(1-2b(i))\right]$$

### 5.1.3 QPSK

In case of QPSK modulation, pairs of bits, $b(2i), b(2i+1)$, are mapped to complex-valued modulation symbols $d(i)$ according to

$$d(i) = \frac{1}{\sqrt{2}}\left[(1-2b(2i)) + j(1-2b(2i+1))\right]$$

### 5.1.4 16QAM

In case of 16QAM modulation, quadruplets of bits, $b(4i), b(4i+1), b(4i+2), b(4i+3)$ , are mapped to complex-valued modulation symbols $d(i)$ according to

$$d(i)=\frac{1}{\sqrt{10}}\left\{(1-2b(4i))\left[2-(1-2b(4i+2))\right]+j(1-2b(4i+1))\left[2-(1-2b(4i+3))\right]\right\}$$

### 5.1.5 64QAM

In case of 64QAM modulation, hextuplets of bits, $b(6i), b(6i+1), b(6i+2), b(6i+3), b(6i+4), b(6i+5)$ , are mapped to complex-valued modulation symbols $d(i)$ according to

$$d(i)=\frac{1}{\sqrt{42}}\left\{(1-2b(6i))\left[4-(1-2b(6i+2))\left[2-(1-2b(6i+4))\right]\right]+j(1-2b(6i+1))\left[4-(1-2b(6i+3))\left[2-(1-2b(6i+5))\right]\right]\right\}$$

### 5.1.6 256QAM

In case of 256QAM modulation, octuplets of bits, $b(8i), b(8i+1), b(8i+2), b(8i+3), b(8i+4), b(8i+5), b(8i+6), b(8i+7)$ , are mapped to complex-valued modulation symbols $d(i)$ according to

$$\begin{aligned}d(i)=\frac{1}{\sqrt{170}}\Big\{&(1-2b(8i))\left[8-(1-2b(8i+2))\left[4-(1-2b(8i+4))\left[2-(1-2b(8i+6))\right]\right]\right]\\&+j(1-2b(8i+1))\left[8-(1-2b(8i+3))\left[4-(1-2b(8i+5))\left[2-(1-2b(8i+7))\right]\right]\right]\Big\}\end{aligned}$$

## Claim 5

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| 5. The method as recited in claim 1, wherein said modified forward path data signal includes at least one type of data selected from a group of different types of data comprising Orthogonal Frequency Division Multiplexing (OFDM) data and Quadrature Phase Shift Keying (QPSK) data. | The Accused Products/Instrumentalities perform the method as recited in claim 1, wherein said forward path data signal includes at least one type of data selected from a group of different types of data comprising Orthogonal Frequency Division Multiplexing (OFDM) data and Quadrature Phase Shift Keying (QPSK) data. For example, the exemplary modified forward path data signals includes at least OFDM data in 5G communications. See claim 1 and evidence therein.<br><br>For example, downlink transmissions from the base station that use beamforming include data selected from OFDM data and QPSK data, such as symbols (e.g., QPSK symbols) on subcarriers of the OFDM system. |

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| | See, e.g., 3GPP TS 38.211 version 15.8.0:<br><br>**5.3.1 OFDM baseband signal generation for all channels except PRACH**<br><br>The time-continuous signal $s_l^{(p,\mu)}(t)$ on antenna port $p$ and subcarrier spacing configuration $\mu$ for OFDM symbol $l \in \{0,1,\ldots,N_{\mathrm{slot}}^{\mathrm{subframe},\mu} N_{\mathrm{symb}}^{\mathrm{slot}} - 1\}$ in a subframe for any physical channel or signal except PRACH is defined by<br><br>$$s_l^{(p,\mu)}(t) = \sum_{k=0}^{N_{\mathrm{grid}}^{\mathrm{size},\mu} N_{\mathrm{sc}}^{\mathrm{RB}} - 1} a_{k,l}^{(p,\mu)} \cdot e^{j2\pi\left(k + k_0^{\mu} - N_{\mathrm{grid},x}^{\mathrm{size},\mu} N_{\mathrm{sc}}^{\mathrm{RB}}/2\right)\Delta f\left(t - N_{\mathrm{CP},l}^{\mu} T_{\mathrm{c}} - t_{\mathrm{start},l}^{\mu}\right)}$$<br>$$k_0^{\mu} = \left(N_{\mathrm{grid},x}^{\mathrm{start},\mu} + N_{\mathrm{grid},x}^{\mathrm{size},\mu}/2\right) N_{\mathrm{sc}}^{\mathrm{RB}} - \left(N_{\mathrm{grid},x}^{\mathrm{start},\mu_0} + N_{\mathrm{grid},x}^{\mathrm{size},\mu_0}/2\right) N_{\mathrm{sc}}^{\mathrm{RB}} 2^{\mu_0 - \mu}$$<br><br>where $t_{\mathrm{start},l}^{\mu} \le t < t_{\mathrm{start},l}^{\mu} + \left(N_{\mathrm{u}}^{\mu} + N_{\mathrm{CP},l}^{\mu}\right) T_{\mathrm{c}}$ is the time within the subframe,<br><br>$$N_{\mathrm{u}}^{\mu} = 2048\kappa \cdot 2^{-\mu}$$<br>$$N_{\mathrm{CP},l}^{\mu} = \begin{cases} 512\kappa \cdot 2^{-\mu} & \text{extended cyclic prefix} \\ 144\kappa \cdot 2^{-\mu} + 16\kappa & \text{normal cyclic prefix, } l = 0 \text{ or } l = 7 \cdot 2^{\mu} \\ 144\kappa \cdot 2^{-\mu} & \text{normal cyclic prefix, } l \neq 0 \text{ and } l \neq 7 \cdot 2^{\mu} \end{cases}$$<br><br>and<br><br>- $\Delta f$ is given by clause 4.2;<br><br>**5.1 Modulation mapper**<br><br>The modulation mapper takes binary digits, 0 or 1, as input and produces complex-valued modulation symbols as output. |

### 5.1.1 π/2-BPSK

In case of $\pi/2$-BPSK modulation, bit $b(i)$ is mapped to complex-valued modulation symbol $d(i)$ according to

$$d(i) = \frac{e^{j\frac{\pi}{2}(i \bmod 2)}}{\sqrt{2}}\left[(1-2b(i)) + j(1-2b(i))\right]$$

### 5.1.2 BPSK

In case of BPSK modulation, bit $b(i)$ is mapped to complex-valued modulation symbol $d(i)$ according to

$$d(i) = \frac{1}{\sqrt{2}}\left[(1-2b(i)) + j(1-2b(i))\right]$$

### 5.1.3 QPSK

In case of QPSK modulation, pairs of bits, $b(2i), b(2i+1)$, are mapped to complex-valued modulation symbols $d(i)$ according to

$$d(i) = \frac{1}{\sqrt{2}}\left[(1-2b(2i)) + j(1-2b(2i+1))\right]$$

### 5.1.4 16QAM

In case of 16QAM modulation, quadruplets of bits, $b(4i), b(4i+1), b(4i+2), b(4i+3)$ , are mapped to complex-valued modulation symbols $d(i)$ according to

$$d(i) = \frac{1}{\sqrt{10}}\left\{(1-2b(4i))\left[2-(1-2b(4i+2))\right] + j(1-2b(4i+1))\left[2-(1-2b(4i+3))\right]\right\}$$

### 5.1.5 64QAM

In case of 64QAM modulation, hextuplets of bits, $b(6i), b(6i+1), b(6i+2), b(6i+3), b(6i+4), b(6i+5)$ , are mapped to complex-valued modulation symbols $d(i)$ according to

$$d(i) = \frac{1}{\sqrt{42}}\left\{(1-2b(6i))\left[4-(1-2b(6i+2))\left[2-(1-2b(6i+4))\right]\right] + j(1-2b(6i+1))\left[4-(1-2b(6i+3))\left[2-(1-2b(6i+5))\right]\right]\right\}$$

### 5.1.6 256QAM

In case of 256QAM modulation, octuplets of bits, $b(8i), b(8i+1), b(8i+2), b(8i+3), b(8i+4), b(8i+5), b(8i+6), b(8i+7)$ , are mapped to complex-valued modulation symbols $d(i)$ according to

$$\begin{aligned} d(i) = \frac{1}{\sqrt{170}}\Big\{&(1-2b(8i))\left[8-(1-2b(8i+2))\left[4-(1-2b(8i+4))\left[2-(1-2b(8i+6))\right]\right]\right] \\ &+ j(1-2b(8i+1))\left[8-(1-2b(8i+3))\left[4-(1-2b(8i+5))\left[2-(1-2b(8i+7))\right]\right]\right]\Big\} \end{aligned}$$

# Claim 6

<table>
<tr>
<td>6. The method as recited in claim 5, wherein said modified forward path data signal includes sub-carrier pre-equalized OFDM data.</td>
<td>

The Accused Products/Instrumentalities perform method as recited in claim 5, wherein said modified forward path data signal includes sub-carrier pre-equalized OFDM data. This is illustrated, for example, in the chart for claim 1, and the 3GPP technical specifications and other documentation cited there and incorporated by reference.

For example, the base station beamforming precoding modifies downlink transmission symbols using precoding ("pre-equalization") and the modified downlink transmission symbols are mapped onto resource elements of the OFDM symbols comprising subcarriers.

See, e.g., 3GPP TS 38.211 version 15.8.0:

### 5.3.1 OFDM baseband signal generation for all channels except PRACH

The time-continuous signal $s_l^{(p,\mu)}(t)$ on antenna port $p$ and subcarrier spacing configuration $\mu$ for OFDM symbol $l \in \{0,1,...,N_{\text{slot}}^{\text{subframe},\mu} N_{\text{symb}}^{\text{slot}} - 1\}$ in a subframe for any physical channel or signal except PRACH is defined by

$$s_l^{(p,\mu)}(t) = \sum_{k=0}^{N_{\text{grid}}^{\text{size},\mu} N_{\text{sc}}^{\text{RB}} - 1} a_{k,l}^{(p,\mu)} \cdot e^{j2\pi\left(k + k_0^\mu - N_{\text{grid},x}^{\text{size},\mu} N_{\text{sc}}^{\text{RB}}/2\right)\Delta f\left(t - N_{\text{CP},l}^\mu T_c - t_{\text{start},l}^\mu\right)}$$

$$k_0^\mu = \left(N_{\text{grid},x}^{\text{start},\mu} + N_{\text{grid},x}^{\text{size},\mu}/2\right) N_{\text{sc}}^{\text{RB}} - \left(N_{\text{grid},x}^{\text{start},\mu_0} + N_{\text{grid},x}^{\text{size},\mu_0}/2\right) N_{\text{sc}}^{\text{RB}} 2^{\mu_0 - \mu}$$

where $t_{\text{start},l}^\mu \le t < t_{\text{start},l}^\mu + \left(N_u^\mu + N_{\text{CP},l}^\mu\right) T_c$ is the time within the subframe,

$$N_u^\mu = 2048\kappa \cdot 2^{-\mu}$$

$$N_{\text{CP},l}^\mu = \begin{cases} 512\kappa \cdot 2^{-\mu} & \text{extended cyclic prefix} \\ 144\kappa \cdot 2^{-\mu} + 16\kappa & \text{normal cyclic prefix, } l = 0 \text{ or } l = 7 \cdot 2^\mu \\ 144\kappa \cdot 2^{-\mu} & \text{normal cyclic prefix, } l \ne 0 \text{ and } l \ne 7 \cdot 2^\mu \end{cases}$$

and

- $\Delta f$ is given by clause 4.2;

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</table>

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| | 7.3.1.5 Mapping to virtual resource blocks<br><br>The UE shall, for each of the antenna ports used for transmission of the physical channel, assume the block of complex-valued symbols $y^{(p)}(0), \ldots, y^{(p)}(M_{\mathrm{symb}}^{\mathrm{ap}} - 1)$ conform to the downlink power allocation specified in [6, TS 38.214] and are mapped in sequence starting with $y^{(p)}(0)$ to resource elements $(k', l)_{p,\mu}$ in the virtual resource blocks assigned for transmission which meet all of the following criteria:<br><br>- they are in the virtual resource blocks assigned for transmission;<br>- the corresponding physical resource blocks are declared as available for PDSCH according to clause 5.1.4 of [6, TS 38.214];<br>- the corresponding resource elements in the corresponding physical resource blocks are<br>  - not used for transmission of the associated DM-RS or DM-RS intended for other co-scheduled UEs as described in clause 7.4.1.1.2;<br>  - not used for non-zero-power CSI-RS according to clause 7.4.1.5 if the corresponding physical resource blocks are for PDSCH scheduled by PDCCH with CRC scrambled by C-RNTI, MCS-C-RNTI, CS-RNTI, or PDSCH with SPS, except if the non-zero-power CSI-RS is a CSI-RS configured by the higher-layer parameter *CSI-RS-Resource-Mobility* in the *MeasObjectNR* IE or except if the non-zero-power CSI-RS is an aperiodic non-zero-power CSI-RS resource;<br>  - not used for PT-RS according to clause 7.4.1.2;<br>  - not declared as 'not available for PDSCH according to clause 5.1.4 of [6, TS 38.214].<br><br>The mapping to resource elements $(k', l)_{p,\mu}$ allocated for PDSCH according to [6, TS 38.214] and not reserved for other purposes shall be in increasing order of first the index $k'$ over the assigned virtual resource blocks, where $k' = 0$ is the first subcarrier in the lowest-numbered virtual resource block assigned for transmission, and then the index $l$ .<br><br>See https://www.sharetechnote.com/html/5G/5G_CSI_RS_Codebook.html:<br><br>**What is Codebook ?** |

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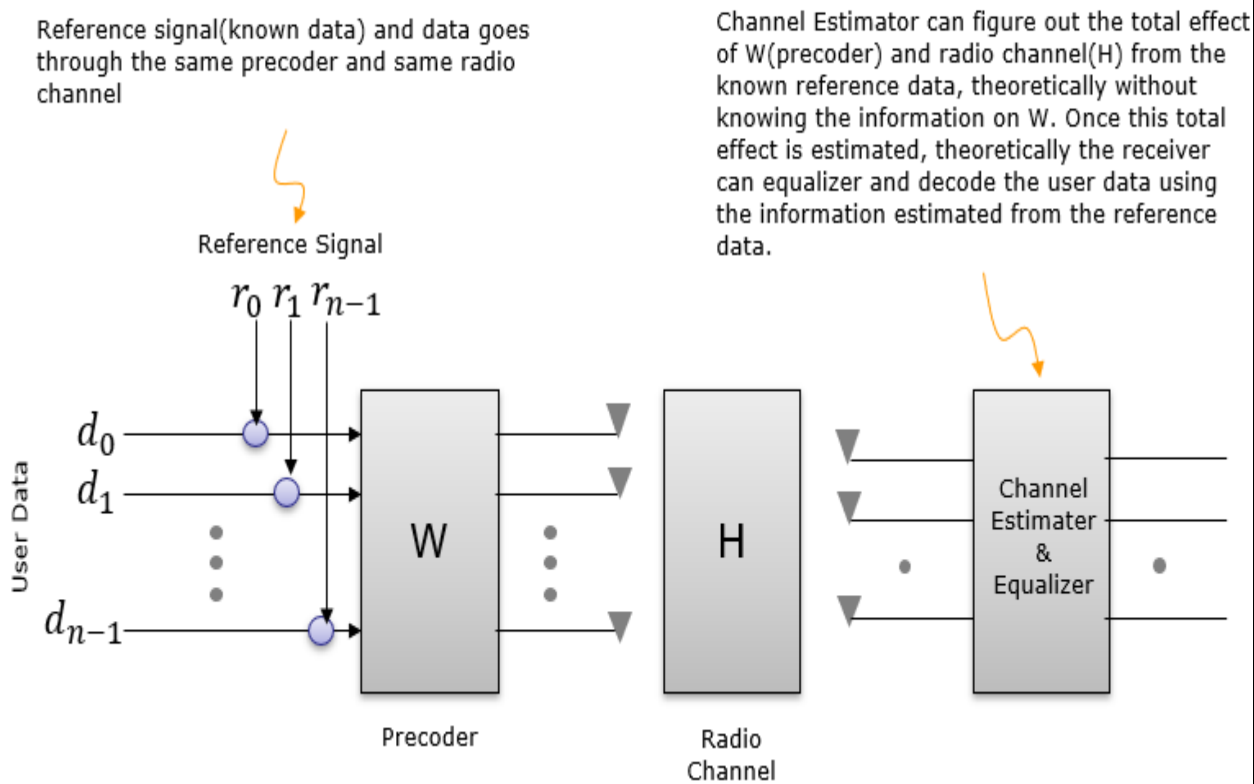
| | What is Codebook ? It would many different things in different situation, but the meaning of Codebook under the context of CSI-RS is a set of Precoders (a set of Precoding Matrix). Putting it other way, Codebook is a kind of matrix (a matrix having complex value elements) that transform the data bit (PDSCH) to another set of data that maps to each antenna port. …  |

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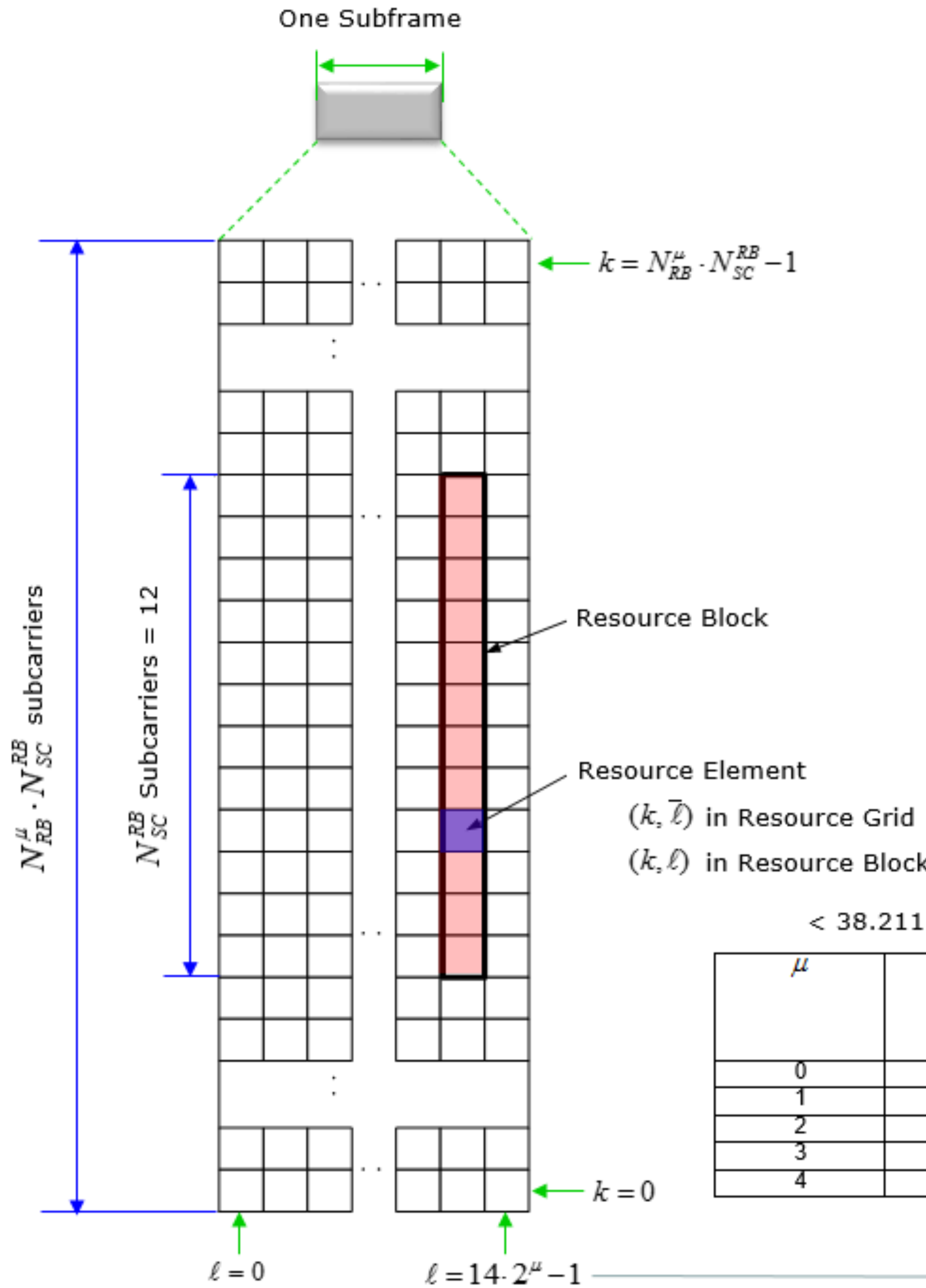
| | See https://www.sharetechnote.com/html/5G/5G_ResourceGrid.html:<br><br>**Resource Grid**<br><br>The resource grid for NR is defined as follows. If you just take a look at the picture, you would think it is almost identical to LTE resource grid. But the physical dimension (i.e., subcarrier spacing, number of OFDM symbols within a radio frame) varies in NR depending on numerology. |




< 38.211-Table 4.2.2-1 >

| $\mu$ | Slot configu… 0 | |
|---|---|---|
| | $N_{\text{symb}}^{\mu}$ | $N_{\text{frame}}^{\text{slot}}$… |
| 0 | 14 | 10 |
| 1 | 14 | 20 |
| 2 | 14 | 40 |
| 3 | 14 | 80 |
| 4 | 14 | 16 |

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| | **Resource Element** : This is same as LTE. It is the smallest unit of the resource grid made up of one subcarrier in frequency domain and one OFDM symbol in time domain.<br><br>**Resource Block**: In NR, Resource Block is defined only for frequency domain. 38.211-4.4.4.1 states *'A resource block is defined as 12(N_RB_sc) consecutive subcarriers in the frequency domain'*.<br>Time domain definition of resource block is a little bit ambiguous. Minimum time domain length in a resource block can be one OFDM symbol, but exact time domain length vary depending SLIV.<br><br>**Resource Grid and Antenna port and Numerology** : Basically one resource grid is created for one antenna port and numerology. 38.211-4.2.2 states as follows.<br>• *There is one set of resource grids per transmission direction (uplink or downlink) with the subscript set to DL and UL for downlink and uplink*<br>• *There is one resource grid for a given antenna port p , subcarrier spacing configuration u, and transmission direction (downlink or uplink).*<br><br>The maximum and minimum number of Resource blocks for downlink and uplink is defined as below (this is different from LTE)<br><br>< 38.211 Table 4.4.2-1: Minimum and maximum number of resource blocks.> |

| $\mu$ | $N_{RB,DL}^{min,\mu}$ | $N_{RB,DL}^{max,\mu}$ | $N_{RB,UL}^{min,\mu}$ | $N_{RB,UL}^{max,\mu}$ |
|---|---|---|---|---|
| 0 | 24 | 275 | 24 | 275 |
| 1 | 24 | 275 | 24 | 275 |
| 2 | 24 | 275 | 24 | 275 |
| 3 | 24 | 275 | 24 | 275 |
| 4 | 24 | 138 | 24 | 138 |

## Claim 7

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| 7. The method as recited in claim 6, further comprising generating corresponding Quadrature Phase Shift Keying (QPSK) modulation values based on said sub-carrier pre-equalized OFDM data. | The Accused Products/Instrumentalities perform the method as recited in claim 6, further comprising generating corresponding Quadrature Phase Shift Keying (QPSK) modulation values based on said sub-carrier pre-equalized OFDM data. This is illustrated, for example, in the chart for claim 1, and the 3GPP technical specifications and other documentation cited there and incorporated by reference.<br><br>For example, the base station maps a sequence of data to QPSK modulation symbol(s), modifying the symbols using precoding (pre-equalization), and mapping the modified symbols onto resource elements (e.g. subcarriers) of the OFDM symbols.<br><br>See, e.g., 3GPP TS 38.211 version 15.8.0:<br><br>**5.3.1 OFDM baseband signal generation for all channels except PRACH**<br><br>The time-continuous signal $s_l^{(p,\mu)}(t)$ on antenna port $p$ and subcarrier spacing configuration $\mu$ for OFDM symbol $l \in \{0,1,...,N_{\text{slot}}^{\text{subframe},\mu} N_{\text{symb}}^{\text{slot}} - 1\}$ in a subframe for any physical channel or signal except PRACH is defined by<br><br>$$s_l^{(p,\mu)}(t) = \sum_{k=0}^{N_{\text{grid}}^{\text{size},\mu} N_{\text{sc}}^{\text{RB}} - 1} a_{k,l}^{(p,\mu)} \cdot e^{j2\pi\left(k + k_0^\mu - N_{\text{grid},x}^{\text{size},\mu} N_{\text{sc}}^{\text{RB}}/2\right)\Delta f\left(t - N_{\text{CP},l}^\mu T_c - t_{\text{start},l}^\mu\right)}$$<br>$$k_0^\mu = \left(N_{\text{grid},x}^{\text{start},\mu} + N_{\text{grid},x}^{\text{size},\mu}/2\right) N_{\text{sc}}^{\text{RB}} - \left(N_{\text{grid},x}^{\text{start},\mu_0} + N_{\text{grid},x}^{\text{size},\mu_0}/2\right) N_{\text{sc}}^{\text{RB}} 2^{\mu_0 - \mu}$$<br><br>where $t_{\text{start},l}^\mu \le t < t_{\text{start},l}^\mu + \left(N_u^\mu + N_{\text{CP},l}^\mu\right) T_c$ is the time within the subframe,<br><br>$$N_u^\mu = 2048\kappa \cdot 2^{-\mu}$$<br>$$N_{\text{CP},l}^\mu = \begin{cases} 512\kappa \cdot 2^{-\mu} & \text{extended cyclic prefix} \\ 144\kappa \cdot 2^{-\mu} + 16\kappa & \text{normal cyclic prefix, } l = 0 \text{ or } l = 7 \cdot 2^\mu \\ 144\kappa \cdot 2^{-\mu} & \text{normal cyclic prefix, } l \ne 0 \text{ and } l \ne 7 \cdot 2^\mu \end{cases}$$<br><br>and<br><br>- $\Delta f$ is given by clause 4.2; |

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| | **5.1 Modulation mapper**<br><br>The modulation mapper takes binary digits, 0 or 1, as input and produces complex-valued modulation symbols as output.<br><br>**5.1.1 π/2-BPSK**<br><br>In case of π/2-BPSK modulation, bit $b(i)$ is mapped to complex-valued modulation symbol $d(i)$ according to<br><br>$$d(i)=\frac{e^{j\frac{\pi}{2}(i \bmod 2)}}{\sqrt{2}}\left[(1-2b(i))+j(1-2b(i))\right]$$<br><br>**5.1.2 BPSK**<br><br>In case of BPSK modulation, bit $b(i)$ is mapped to complex-valued modulation symbol $d(i)$ according to<br><br>$$d(i)=\frac{1}{\sqrt{2}}\left[(1-2b(i))+j(1-2b(i))\right]$$<br><br>**5.1.3 QPSK**<br><br>In case of QPSK modulation, pairs of bits, $b(2i), b(2i+1)$, are mapped to complex-valued modulation symbols $d(i)$ according to<br><br>$$d(i)=\frac{1}{\sqrt{2}}\left[(1-2b(2i))+j(1-2b(2i+1))\right]$$ |

## Claim 9

| **Claim 9** | Identification |
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| 9. The method as in claim 1, wherein said reveres path data signal includes identifiable training data. | The Accused Products/Instrumentalities perform the method as in claim 1, wherein said reverse path data signal includes identifiable training data. For example, as explained for claim 1, which is incorporated by reference, the base station receives a reverse path data signal such as and/or including, e.g., a Sounding Reference Signal that includes identifiable training data. As another example, the base station receives a reverse path data signal such as and/or including, e.g., UL transmission from UE, including, e.g., CSI measurements such as PMI, that includes identifiable training data. See claim 1 and evidence therein. See, e.g., 3GPP specifications (e.g. 3GPP TS 38.211 v15.8.0) § 6.2, § 6.4.1.4 (Sounding Reference Signal); 38.214 v15.6 § 5.2 (describing CSI). |

## Claim 10

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| 10. The method as recited in claim 9, further comprising: comparing said identifiable training data to a local version of said training data to identify said at least one multipath transmission delay within said reverse path data signal. | The Accused Products/Instrumentalities perform the method as in claim 9, wherein said reverse path data signal includes identifiable training data, and further comprising comparing said identifiable training data to a local version of said training data to identify said at least one multipath transmission delay within said reverse path data signal. For example, as explained for claim 1, which is incorporated by reference, the base station receives a reverse path data signal such as and/or including, e.g., a Sounding Reference Signal that includes identifiable training data. As another example, the base station receives a reverse path data signal such as and/or including, e.g., UL transmission from UE, including, e.g., following CSI-RS, CSI measurements such as PMI, that includes identifiable training data. As an example, the base station compares the Sounding Reference Signal to a local version to identify said at least one multipath transmission delay. As another example, with CSI-RS procedures, the base station compares (e.g., PMI) to a local version to identify said at least one multipath transmission delay within said reverse path data signal. See claim 1 and evidence therein.<br><br>For example, the base station may compare the received SRS signal with a local version that is a known SRS reference signal to estimate the channel (e.g., channel multipath delay profile) using, e.g., correlation techniques.<br><br>https://www.sharetechnote.com/html/5G/5G_SRS.html<br><br>**Phase I** - RRC Configuration for SRS<br>This is the phase where gNB determines about SRS configuration (e.g., SRS physical resources, usage, report period timing etc.) and notifies the configuration to UE via RRC messages (e.g., RRCSetup, RRCReconfiguration).<br>**Phase II** - SRS transmission from UE:<br>In this phase, the UE transmits the SRS, which is a predefined signal with known characteristics, at a specific time and frequency. The SRS configuration is provided to the UE by the gNB, and it may vary depending on the cell's conditions and traffic requirements. The UE sends the SRS periodically or aperiodically, as instructed by the gNB, on the uplink (UL) channel.<br>**NOTE** : gNB can configure UE to transmit the srs across the full band at once or can configure UE to transmit the srs for a certain segment of the frequency band using the parameter explained in Bandwidth Configuration.<br>**NOTE** : gNB configures how often and at which timing UE should send SRS. gNB would get better and more accurate information as it let UE to transmit more often for wider frequency span, but overhead caused by srs transmission would get higher.<br>**Phase III** - SRS reception at gNB and Analysis: |

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| | Upon receiving the SRS from the UE, the gNB measures and analyzes the received signal. It estimates the channel state information (CSI) by comparing the received SRS with the known reference signal. The gNB evaluates various parameters, such as the path loss, propagation delay(phase delay), and received signal strength, to understand the current radio environment and channel conditions between the gNB and the UE.<br><br>https://telcomaglobal.com/p/5g-nr-srs-sounding-reference-signals<br><br>**5G NR SRS (Sounding Reference Signals)**<br><br>Introduction<br><br>SRS is Sounding Reference Signal is a reference signal transmitted by the UE in the uplink direction which is used by the eNodeB to estimate the uplink channel quality over a wider bandwidth. SRS is a UL reference signal which is transmitted by UE to the base station. SRS gives information about the combined effect of multipath fading, scattering, Doppler, and power loss of the transmitted signal. Sounding reference signals are uplink physical signals employed by user equipment (UE) for uplink channel sounding, including channel quality estimation and synchronization. Unlike Demodulation reference signals (DM-RS), SRS is not associated with any physical uplink channels, and they support uplink channel-dependent scheduling and link adaptation. SRS assist in:<br><br>• Codebook-based closed-loop spatial multiplexing<br>• Control uplink transmit timing<br>• Reciprocity-based downlink precoding in multi-user MIMO setups<br>• Quasi co-location of physical channels and reference signals<br><br>In 5G NR, the SRS is transmitted by the UE for uplink channel sounding, which includes channel estimation and synchronization. An NR-SRS is an uplink orthogonal frequency division multiplexing (OFDM) signal filled with a Zadoff-Chu sequence on different subcarriers. For the purposes of communications, the SRS is used for closed-loop spatial multiplexing, uplink transmitting timing control, and reciprocity multi-user downlink precoding. To utilize the channel sounding function, the SRS must be known by both the UE and the gNB. UE act as a mobile transmitter and gNB act as a base station receiver.<br><br>Base station estimates the channel quality using this reference signal and manages further resource scheduling, Beam management, and power control of the signal. So SRS provides information to gNB about the channel over the full bandwidth and using this information, gNB takes decisions for resource allocation which has better channel quality as compared to other Bandwidth regions. |

# Claim 12

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| 12. The method as recited in claim 3, wherein said at least one reverse transmission path is substantially reciprocal to said at least one forward transmission path. | The Accused Products/Instrumentalities perform the method as recited in claim 3, wherein said at least one reverse transmission path is substantially reciprocal to said at least one forward transmission path. For example, in the TDD example described for claim 1, at least one reverse transmission path is substantially reciprocal to said at least one forward transmission path. See claim 1 and evidence therein. For example, in TDD, downlink and uplink propagation paths are reciprocal and experience the same multipath delay profile.<br><br>Ericsson White Paper on Advanced Antenna Systems for 5G Networks (publication, including contributors Peter von Butovitsch, David Astely, Christer Friberg, Anders Furuskär, Bo Göransson, Billy Hogan, Jonas Karlsson and Erik Larsson):<br><br>See https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks (also available at https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks):<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short- term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics.<br><br>https://www.mathworks.com/help/5g/ug/tdd-reciprocity-based-pdsch-beamforming-using-srs.html |

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| | **TDD Reciprocity-Based PDSCH MU-MIMO Using SRS**<br><br>This example implements downlink multiuser multiple-input multiple-output (MU-MIMO) by exploiting channel reciprocity in a time division duplex (TDD) scenario. The example shows how to determine beamforming weights for physical downlink shared channel (PDSCH) transmission by using channel estimates based on uplink sounding reference signals (SRS) transmitted for each user, and how to schedule PDSCHs for multiple users in the same time and frequency resources.<br><br>Introduction<br><br>TDD systems use the same frequency band for uplink (UL) and downlink (DL) transmissions. The radio channel is reciprocal because it has the same characteristics in both UL and DL directions. Exploiting this reciprocity, you can use a UL transmission to obtain a channel estimate and then use this channel estimate to calculate parameters, including beamforming, for a DL transmission. This method is known as reciprocity-based beamforming.<br><br>This example implements downlink MU-MIMO by calculating a channel estimate for multiple users based on their SRS transmissions. Assuming reciprocity, the example then uses these channel estimates to select a set of users to be scheduled for PDSCH transmission and calculates DL beamforming weights for PDSCH transmissions to those users. When the base station has a sufficient number of antennas, it is possible to beamform PDSCH transmissions for a set of users in the same time and frequency resources such that the users suffer little interference from each other.<br><br>This example schedules SRS transmissions for all UEs in the UL part of the special slot, and schedules PDSCH transmissions for UEs chosen by the user selection algorithm in DL slots and the DL part of special slots<br><br>Further, the following web pages describe FDD / TDD carrier aggregation and TDD deployment.<br>https://www.ericsson.com/en/blog/2021/6/what-why-how-5g-carrier-aggregation<br><br>https://www.rcrwireless.com/20220111/test-and-measurement/srg-tests-t-mos-fdd-tdd-ca-you-can-have-your-cake-and-eat-it-too |

| | |
|---|---|
| | https://www.rcrwireless.com/20220407/featured/how-will-3gpp-release-17-enhance-channel-reciprocity |

## Claim 13

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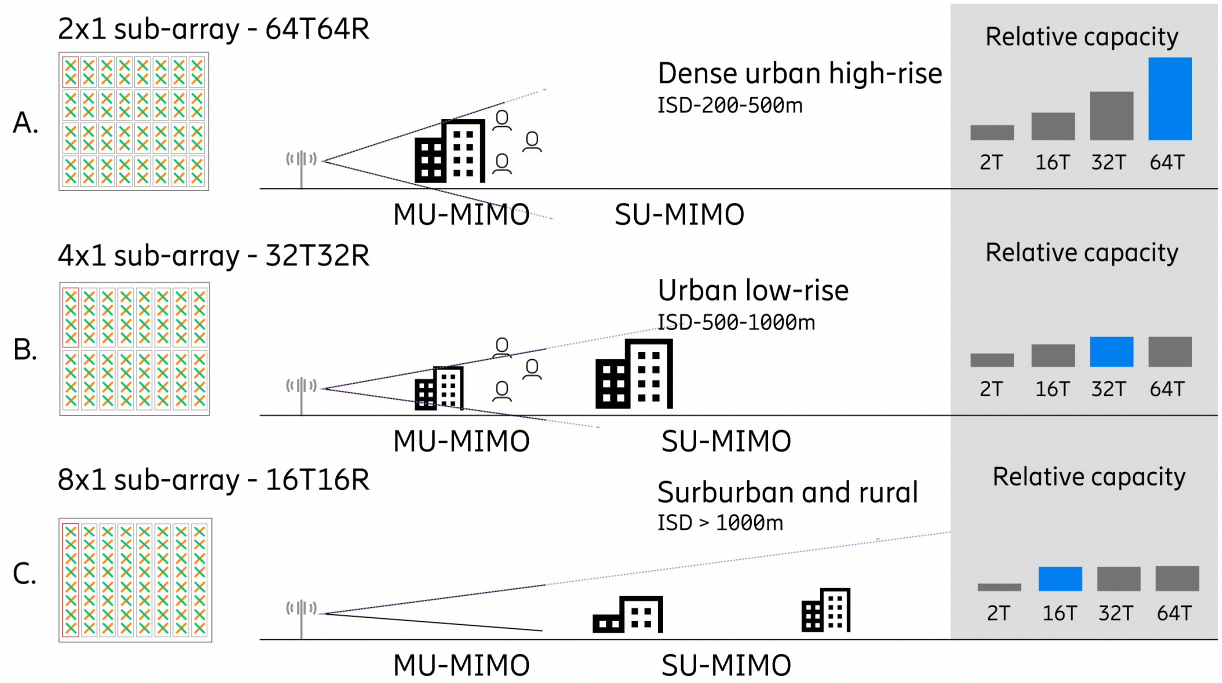
| 13. The method as recited in claim 1, wherein identifying said at least one multipath transmission delay, determining said at least one forward path pre-equalization parameter, and modifying said forward path data signal are performed by a transmitting device. | The Accused Products/Instrumentalities perform the method as recited in claim 1, wherein identifying said at least one multipath transmission delay, determining said at least one forward path pre-equalization parameter, and modifying said forward path data signal are performed by a transmitting device. For example, a Ericsson and/or Nokia RAN solution includes a base station that includes a transmitting device. See evidence for 1[pre] above.<br><br>See https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks (also available at https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks) (illustrating Ericsson base stations)<br><br><br> |

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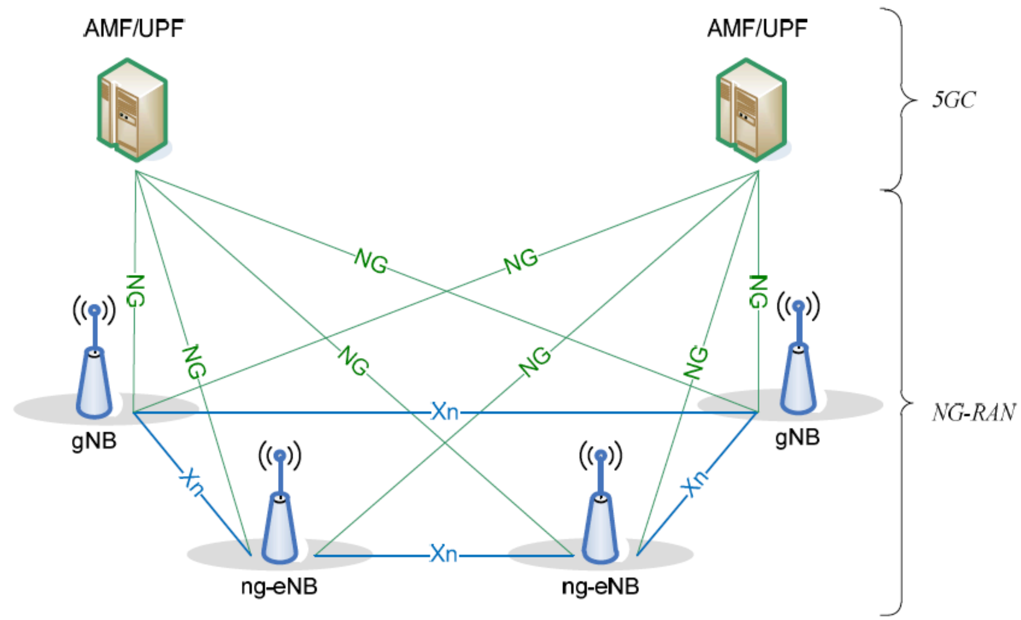
| | See https://www.nokia.com/networks/mobile-networks/airscale-radio-access/ (illustrating Nokia base stations)<br><br>See e.g. 3GPP TS 38.300 v17.2.0, § 4.1.<br><br>The NG-RAN architecture is illustrated in Figure 4.1-1 below.<br><br><br><br>**Figure 4.1-1: Overall Architecture** |

## Claim 14

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| 14. The method as recited in claim 13, wherein said transmitting device includes a base station device that is operatively configured for use in a wireless communication system. | The Accused Products/Instrumentalities perform the method as recited in claim 13, wherein identifying said at least one multipath transmission delay, determining said at least one forward path pre-equalization parameter, and modifying said forward path data signal are performed by a transmitting device, and as recited in claim 14, wherein said transmitting device includes a base station device that is operatively configured for use in a wireless communication system. For example, a Ericsson and/or Nokia RAN solution includes a base station that is a transmitting device and the base station is configured for use in a 5G wireless communications system. See claim 13-14 above and evidence for 1[pre] above. |

## Claim 15

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| 15. The method as recited in claim 13, using at least one transmitting device receive antenna operatively coupled to said transmitting device to receive said reverse path data signal over at least one reverse transmission path from the receiving device. | The Accused Products/Instrumentalities perform the method as recited in claim 13, using at least one transmitting device receive antenna operatively coupled to said transmitting device to receive said reverse path data signal over at least one reverse transmission path from the receiving device. For example, the Ericsson or Nokia base station includes an antenna array coupled to the base station to wirelessly receive the exemplary reverse path data signals described for claim 1 over at least one reverse transmission path from the receiving device. See claim 1 and evidence therein.<br><br>For example, received SRS and/or CSI with PMI (e.g., exemplary "reverse path data signal") are received via a reverse transmission path from the user equipment by at least one base station receive antenna ("transmitting device receive antenna") operatively coupled to the transmitting device ("base station").<br><br>See https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks (also available at https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks) (illustrating Ericsson base stations)<br><br>***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.<br><br>DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, |

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| | generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short- term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics. |

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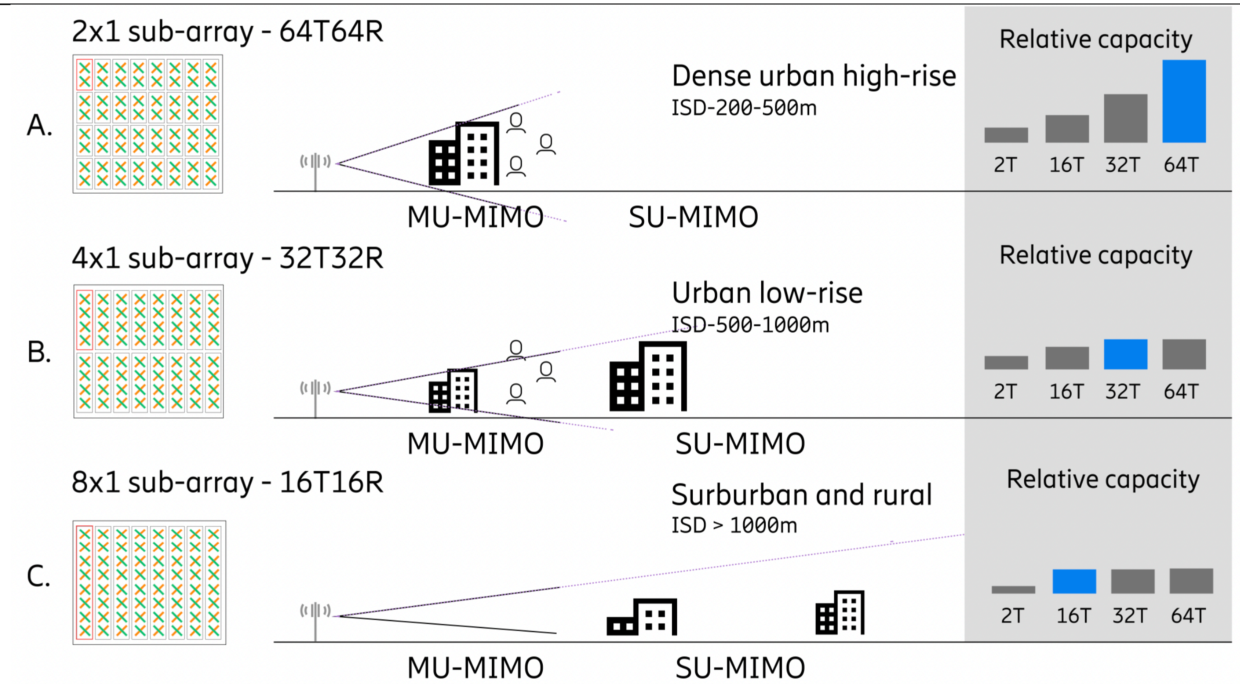
| | <br><br>See https://www.nokia.com/networks/mobile-networks/airscale-radio-access/ (illustrating Nokia base stations)<br><br>See e.g. 3GPP TS 38.300 v17.2.0, § 4.1. |

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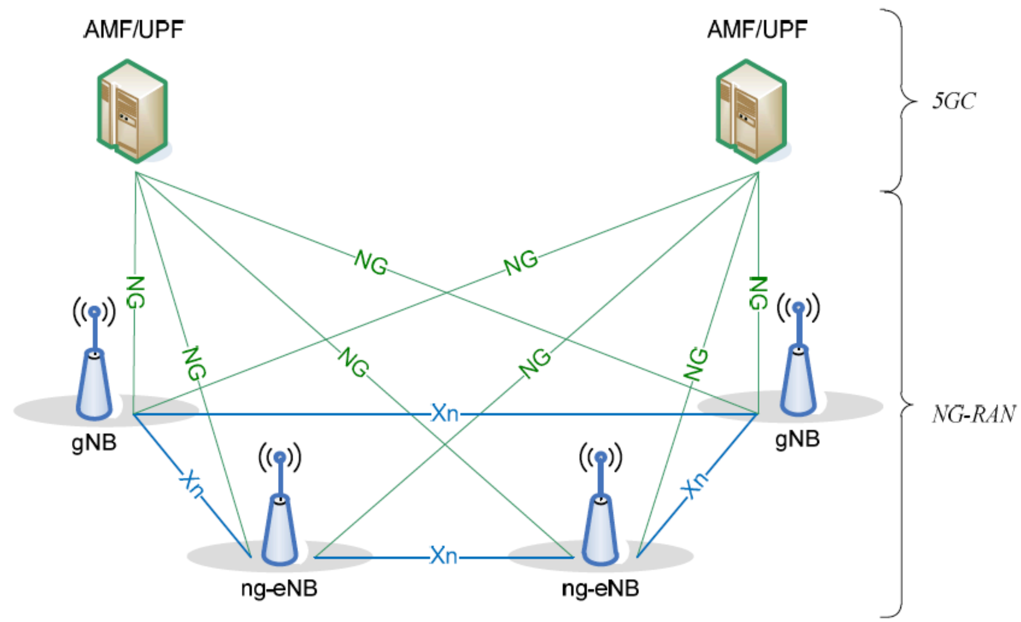
| | The NG-RAN architecture is illustrated in Figure 4.1-1 below.   **Figure 4.1-1: Overall Architecture** |

## Claim 19

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| 19. The method as recited in claim 15, wherein said transmitting device is operatively coupled to a plurality of first device receive antennas. | The Accused Products/Instrumentalities perform the method recited in claim 15, wherein said transmitting device is operatively coupled to a plurality of first device receive antennas. For example, the Ericsson or Nokia base station includes an antenna array coupled to the base station to wirelessly receive the exemplary reverse path data signals described for claim 1 over at least one reverse transmission path from the receiving device. The antenna array includes a plurality of first device receive antennas. See claim 1 and evidence cited therein. For example, the Ericsson and Nokia RAN Solutions with 5G massive MIMO require a large number of receive antennas for beamforming.<br><br>The Accused Products/Instrumentalities perform the method as recited in claim 13, using at least one transmitting device receive antenna operatively coupled to said transmitting device to receive said reverse path data signal over at least one reverse transmission path from the receiving device. For example, the Ericsson or Nokia base station includes an antenna array coupled to the base station to wirelessly receive the exemplary reverse path data signals described for claim 1 over at least one reverse transmission path from the receiving device. See claim 1 and evidence therein.<br><br>For example, received SRS and/or CSI with PMI (e.g., exemplary "reverse path data signal") are received via a reverse transmission path from the user equipment by at least one base station receive antenna ("transmitting device receive antenna") operatively coupled to the transmitting device ("base station").<br><br>See https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks (also available at https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks) (illustrating Ericsson base stations)<br><br>***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and |

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| | DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.<br><br>DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short- term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such |

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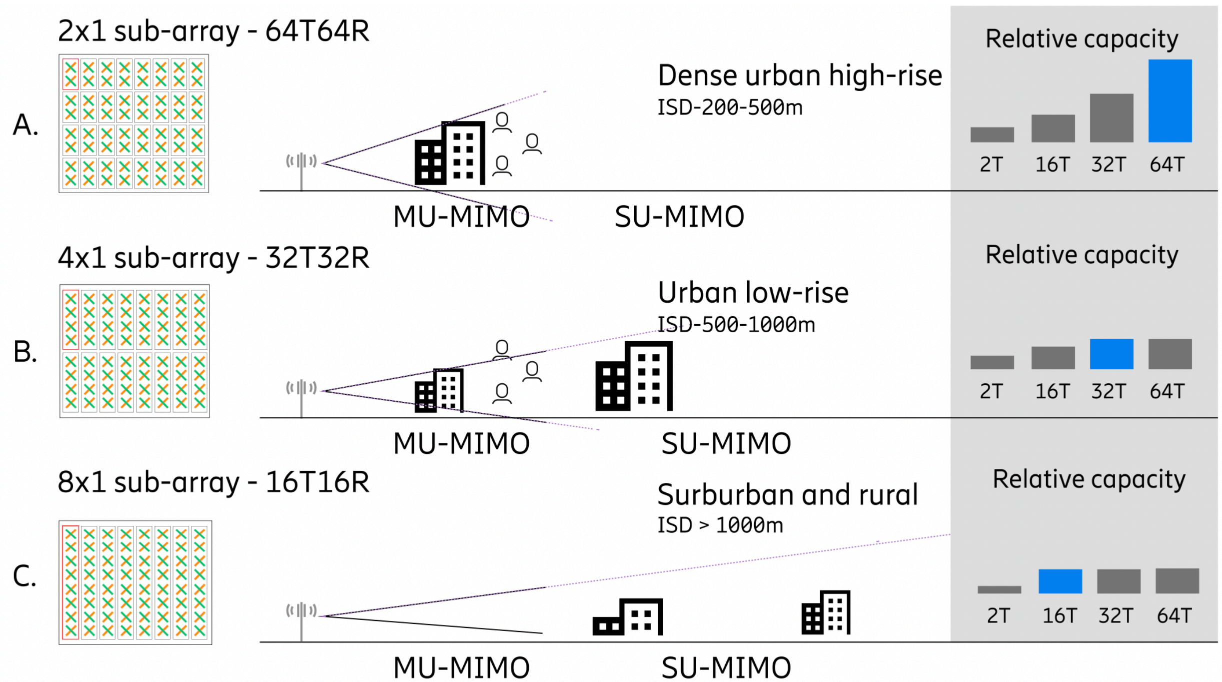
| | as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics.<br><br><br>See https://www.nokia.com/networks/mobile-networks/airscale-radio-access/ (illustrating Nokia base stations)<br>See e.g. 3GPP TS 38.300 v17.2.0, § 4.1. |

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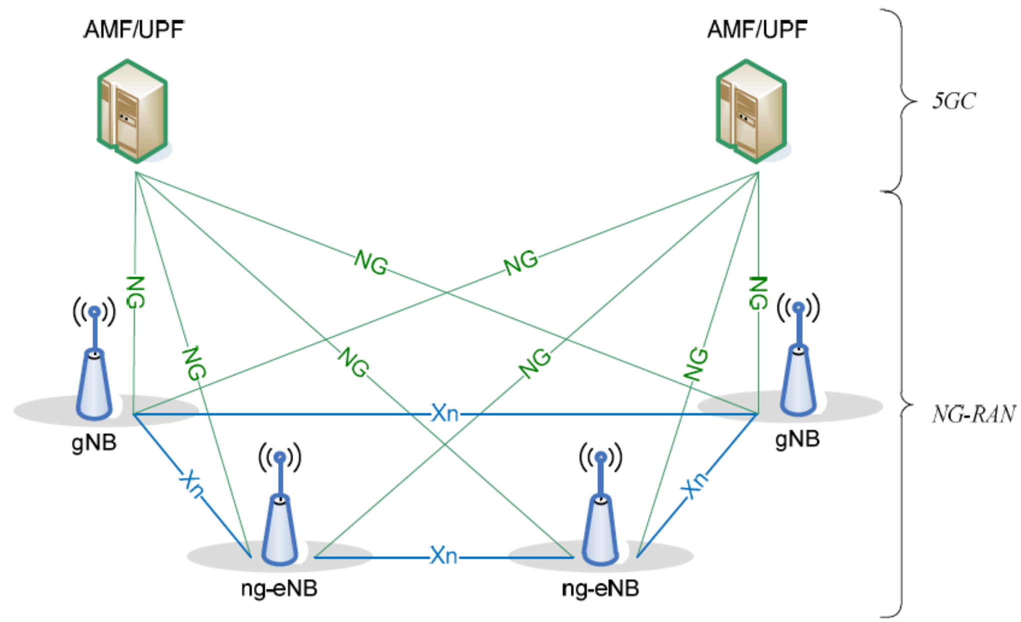
| | The NG-RAN architecture is illustrated in Figure 4.1-1 below.   **Figure 4.1-1: Overall Architecture** |

## Claim 21

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| 21. The method as recited in claim 15, wherein determining said at least one forward path pre-equalization parameter based on said at least one transmission delay further includes:<br>determining at least one angle of arrival of said reverse path data signal with respect to said at least one transmitting device receive antenna. | The Accused Products/Instrumentalities perform the method recited in claim 15, wherein determining said at least one forward path pre-equalization parameter based on said at least one transmission delay further includes: determining at least one angle of arrival of said reverse path data signal with respect to said at least one transmitting device receive antenna. For example, in the TDD example, the base station uses SRS to determine at least one angle of arrival of said reverse path data signal with respect to at least one transmitting device receive antenna of the antenna array of the base station. See claim 1[b] and evidence cited therein.<br><br>As another non-limiting example, in an FDD example, the base station uses CSI such as PMI to determine at least one angle of arrival of said reverse path data signal with respect to said at least one transmitting device receive antenna (base station receive antenna). See claim 1[b] and evidence cited therein.<br><br>As described for 1[b], the base station uses e.g. channel estimation to determine the forward path pre-equalization parameter(s) based on said at least one transmission delay and this process includes determining at least one angle of arrival of said reverse path data signal with respect to said at least one transmitting device receive antenna (base station receive antenna). For example, determining at least one angle of arrival of the SRS or of the signal containing CSI in response to CSI-RS with respect to at least one base station receive antenna.<br><br>See, e.g., Ericsson Advanced Antenna System for 5G Networks white paper / https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks:<br><br>***Key terms***<br>**AAS radio** = Hardware unit that comprises an antenna array, radio chains and parts of the baseband, all tightly integrated to facilitate AAS features<br>**AAS feature** = A multi-antenna feature (such as beamforming and MIMO) that can be executed in the AAS radio, in the baseband unit or both<br>**AAS** = AAS radio + AAS features<br>**Conventional system** = Passive antenna + remote radio unit comprising a low number (2, 4 or 8) of radio chains<br>**Dual-polarized antenna element** = Combination of two antenna elements |

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| | with orthogonal polarizations with the purpose of enabling diversity and doubling the number of antenna elements on a given physical area<br><br>**What is an advanced antenna system?**<br>An advanced antenna system (AAS) is a combination of an AAS radio and a set of AAS features. An AAS radio consists of an antenna array closely integrated with the hardware and software required for transmission and reception of radio signals, and signal processing algorithms to support the execution of the AAS features. Compared to conventional systems, this solution provides much greater adaptivity and steerability, in terms of adapting the antenna radiation patterns to rapidly time-varying traffic and multi-path radio propagation conditions. In addition, multiple signals may be simultaneously received or transmitted with different radiation patterns.<br><br>***Multi-antenna techniques***<br>Multi-antenna techniques, here referred to as AAS features, include beamforming and MIMO. Such features are already used with conventional systems in today's LTE networks. Applying AAS features to an AAS radio results in significant performance gains because of the higher degrees of freedom provided by the larger number of radio chains, also referred to as Massive MIMO.<br><br>**Beamforming**<br>When transmitting, beamforming is the ability to direct radio energy through the radio channel toward a specific receiver, as shown in the top left quadrant of **Figure 1**. By adjusting the phase and amplitude of the transmitted signals, constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput. Similarly, when receiving, beamforming is the ability to collect the signal energy from a specific transmitter. The beams formed by an AAS are constantly adapted to the surroundings to give high performance in both UL and DL.” |

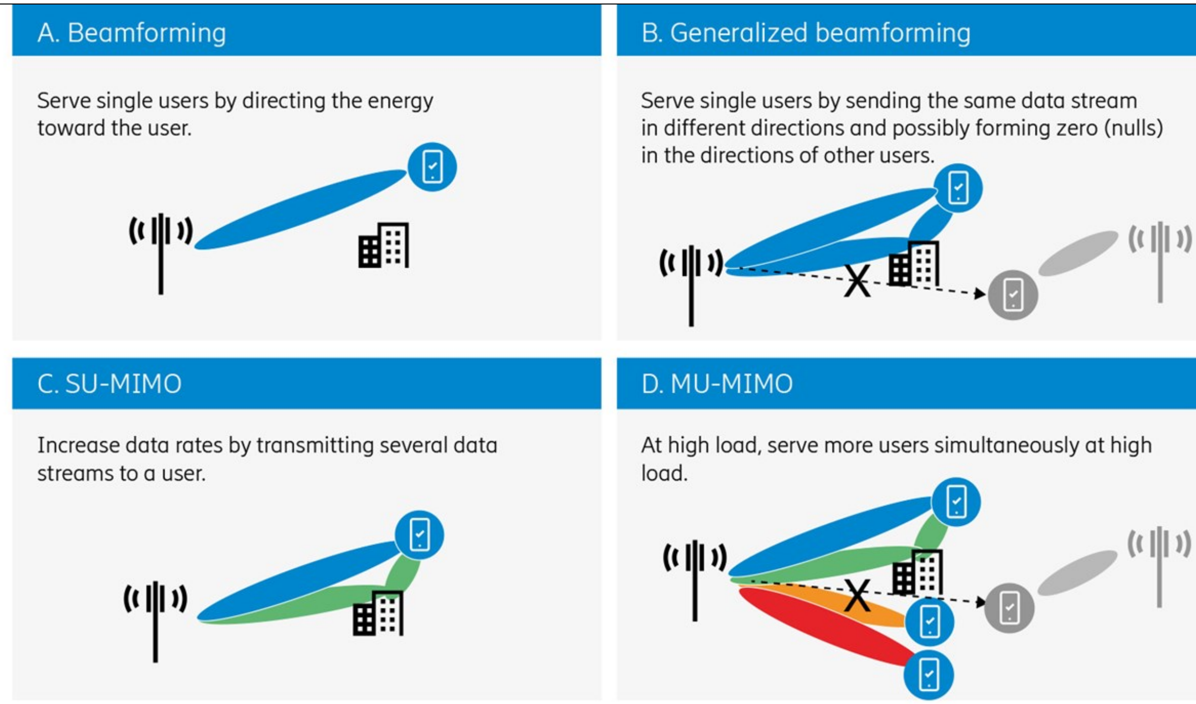


Figure 1: Beamforming and MIMO, with the different colors of the filled beams representing streams.

Although often very effective, transmitting energy in only one direction does not always provide an optimum solution. In multi-path scenarios, where the radio channel comprises multiple propagation paths from transmitter to receiver through diffraction around corners and reflections against buildings or other objects, it is beneficial to send the same data stream in several different paths (direction and/or polarization) with phases and amplitudes controlled in a way that they add constructively at the receiver [5]. This is referred to as generalized beamforming, as shown in the upper right quadrant of Figure 1. As part of generalized beamforming, it is also possible to reduce interference to other UEs, which is known as null forming. This is achieved by

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| | controlling the transmitted signals in a way that they cancel each other out at the interfered UEs.<br><br>**MIMO (Multiple Input, Multiple Output) techniques**<br>Spatial multiplexing, here referred to as MIMO, is the ability to transmit multiple data streams, using the same time and frequency resource, where each data stream can be beamformed. The purpose of MIMO is to increase throughput. MIMO builds on the basic principle that when the received signal quality is high, it is better to receive multiple streams of data with reduced power per stream, than one stream with full power. The potential is large when the received signal quality is high and the streams do not interfere with each other. The potential diminishes when the mutual interference between streams increases. MIMO works in both UL and DL, but for simplicity the description below will be based on the DL.<br><br>Single-user MIMO (SU-MIMO) is the ability to transmit one or multiple data streams, called layers, from one transmitting array to a single user. SU-MIMO can thereby increase the throughput for that user and increase the capacity of the network. The number of layers that can be supported, called the rank, depends on the radio channel. To distinguish between DL layers, a UE needs to have at least as many receiver antennas as there are layers.<br><br>SU-MIMO can be achieved by sending different layers on different polarizations in the same direction. SU-MIMO can also be achieved in a multi path environment, where there are many radio propagation paths of similar strength between the AAS and the UE, by sending different layers on different propagation paths, as shown in the bottom left quadrant of Figure 1.<br><br>In multi-user MIMO (MU-MIMO), which is shown in the bottom right quadrant of Figure 1, the AAS simultaneously sends different layers in separate beams to different users using the same time and frequency resource, thereby increasing the network capacity. In order to use MU-MIMO, the system needs to find two or more users that need to transmit or receive data at the very same time. Also, for efficient MU-MIMO, the |

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| | interference between the users should be kept low. This can be achieved by using generalized beamforming with null forming such that when a layer is sent to one user, nulls are formed in the directions of the other simultaneous users.<br><br>The achievable capacity gains from MU-MIMO depend on receiving each layer with good signal-to-interference-and-noise-ratio (SINR). As with SU-MIMO, the total DL power is shared between the different layers, and therefore the power (and thus SINR) for each user is reduced as the number of simultaneous MU-MIMO users increases. Also, as the number of users grows, the SINR will further deteriorate due to mutual interference between the users. Therefore, the network capacity typically improves as the number of MIMO layers increases, to a point at which power sharing and interference between users result in diminishing gains, and eventually also losses.<br><br>It should be noted that the practical benefits of many layers in MU-MIMO are limited by the fact that, in today's real networks, even with a high number of simultaneous connected users, there tends not to be many users who want to receive data simultaneously. This is due to the bursty (chatty) nature of data transmission to most users. Since the AAS and the transport network must be dimensioned for the maximum number of layers, the MNO needs to consider how many layers are required in their networks. In typical MBB deployments with the current 64T64R AAS variants, the vast majority of the DL and UL capacity gains can be achieved with up to 8 layers."<br><br>***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine |

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| | how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.<br><br>DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short- term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics.<br><br>The suitable channel knowledge scheme to use depends on UL coverage and UE capabilities. In cases where UL coverage is limiting, UE feedback offers a more robust |

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| | operation, whereas full UL channel estimation is applicable in scenarios with good coverage. In short, both reciprocity and UE feedback-based beamforming are needed.<br><br>**Antenna array structure**<br>The purpose of using a rectangular antenna array, as shown in section A of Figure 2, is to enable high-gain beams and make it possible to steer those beams over a range of angles. The gain is achieved, in both UL and DL, by constructively combining signals from a number of antenna elements. The more antenna elements there are, the higher the gain. Steerability is achieved by individually controlling the amplitude and phase of smaller parts of the antenna array. This is usually done by dividing the antenna array into so called sub-arrays (groups of non-overlapping elements), as shown in section C of Figure 2, and by applying two dedicated radio chains per sub-array (one per polarization) to enable control, as shown in section D. In this way it is possible to control the direction and other properties of the created antenna array beam.<br><br>https://www.ericsson.com/4917a1/assets/local/reports-papers/ericsson-technology-review/docs/2022/the-role-of-massive-mimo-in-5g-networks.pdf<br><br>**Multi-antenna technologies**<br><br>Massive MIMO improves network coverage and capacity through the use of the three multi-antenna technologies – beamforming, null forming and spatial multiplexing – shown in *Figure 1*. All three are applicable to both the downlink (DL) and the uplink (UL). The purpose of beamforming is to amplify transmitted/received signals more in some directions than others. The goal is to achieve a high beamforming gain in the direction of the device of interest to improve link quality in terms of signal-to-interference-plus-noise-ratio (SINR). This translates into higher spectral efficiency and/or better coverage for a single link, which in turn results in better network coverage, capacity and user throughput.<br><br>https://www.sharetechnote.com/html/5G/5G_SRS.html<br><br>**Phase I** - RRC Configuration for SRS |

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| | This is the phase where gNB determines about SRS configuration (e.g., SRS physical resources, usage, report period timing etc.) and notifies the configuration to UE via RRC messages (e.g., RRCSetup, RRCReconfiguration).<br>**Phase II** - SRS transmission from UE:<br>In this phase, the UE transmits the SRS, which is a predefined signal with known characteristics, at a specific time and frequency. The SRS configuration is provided to the UE by the gNB, and it may vary depending on the cell's conditions and traffic requirements. The UE sends the SRS periodically or aperiodically, as instructed by the gNB, on the uplink (UL) channel.<br>**NOTE** : gNB can configure UE to transmit the srs across the full band at once or can configure UE to transmit the srs for a certain segment of the frequency band using the parameter explained in Bandwidth Configuration.<br>**NOTE** : gNB configures how often and at which timing UE should send SRS. gNB would get better and more accurate information as it let UE to transmit more often for wider frequency span, but overhead caused by srs transmission would get higher.<br>**Phase III** - SRS reception at gNB and Analysis:<br>Upon receiving the SRS from the UE, the gNB measures and analyzes the received signal. It estimates the channel state information (CSI) by comparing the received SRS with the known reference signal. The gNB evaluates various parameters, such as the path loss, propagation delay(phase delay), and received signal strength, to understand the current radio environment and channel conditions between the gNB and the UE.<br><br>https://telcomaglobal.com/p/5g-nr-srs-sounding-reference-signals<br>**5G NR SRS (Sounding Reference Signals)**<br>Introduction<br>SRS is Sounding Reference Signal is a reference signal transmitted by the UE in the uplink direction which is used by the eNodeB to estimate the uplink channel quality over a wider bandwidth. SRS is a UL reference signal which is transmitted by UE to the base station. SRS gives information about the combined effect of multipath fading, scattering, Doppler, and power loss of the transmitted signal. Sounding reference signals are uplink physical signals employed by user equipment (UE) for uplink channel sounding, including channel quality estimation and synchronization. Unlike Demodulation reference signals (DM-RS), SRS is not associated with any physical uplink channels, and they support uplink channel-dependent scheduling and link adaptation. SRS assist in:<br>• Codebook-based closed-loop spatial multiplexing<br>• Control uplink transmit timing |

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| | • Reciprocity-based downlink precoding in multi-user MIMO setups<br>• Quasi co-location of physical channels and reference signals<br>In 5G NR, the SRS is transmitted by the UE for uplink channel sounding, which includes channel estimation and synchronization. An NR-SRS is an uplink orthogonal frequency division multiplexing (OFDM) signal filled with a Zadoff-Chu sequence on different subcarriers. For the purposes of communications, the SRS is used for closed-loop spatial multiplexing, uplink transmitting timing control, and reciprocity multi-user downlink precoding. To utilize the channel sounding function, the SRS must be known by both the UE and the gNB. UE act as a mobile transmitter and gNB act as a base station receiver.<br>Base station estimates the channel quality using this reference signal and manages further resource scheduling, Beam management, and power control of the signal. So SRS provides information to gNB about the channel over the full bandwidth and using this information, gNB takes decisions for resource allocation which has better channel quality as compared to other Bandwidth regions<br><br>https://www.mathworks.com/help/5g/ug/tdd-reciprocity-based-pdsch-beamforming-using-srs.html<br>**TDD Reciprocity-Based PDSCH MU-MIMO Using SRS**<br>This example implements downlink multiuser multiple-input multiple-output (MU-MIMO) by exploiting channel reciprocity in a time division duplex (TDD) scenario. The example shows how to determine beamforming weights for physical downlink shared channel (PDSCH) transmission by using channel estimates based on uplink sounding reference signals (SRS) transmitted for each user, and how to schedule PDSCHs for multiple users in the same time and frequency resources.<br>**Introduction**<br>TDD systems use the same frequency band for uplink (UL) and downlink (DL) transmissions. The radio channel is reciprocal because it has the same characteristics in both UL and DL directions. Exploiting this reciprocity, you can use a UL transmission to obtain a channel estimate and then use this channel estimate to calculate parameters, including beamforming, for a DL transmission. This method is known as reciprocity-based beamforming. |

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| | This example implements downlink MU-MIMO by calculating a channel estimate for multiple users based on their SRS transmissions. Assuming reciprocity, the example then uses these channel estimates to select a set of users to be scheduled for PDSCH transmission and calculates DL beamforming weights for PDSCH transmissions to those users. When the base station has a sufficient number of antennas, it is possible to beamform PDSCH transmissions for a set of users in the same time and frequency resources such that the users suffer little interference from each other.<br><br>This example schedules SRS transmissions for all UEs in the UL part of the special slot, and schedules PDSCH transmissions for UEs chosen by the user selection algorithm in DL slots and the DL part of special slots<br><br>For example, Ericsson published "How to build high-performing Massive MIMO systems," Billy Hogan, Bo Göransson, Sebastian Faxér, Sibel Tombaz, available athttps://www.ericsson.com/en/blog/2021/2/how-to-build-high-performing-massive-mimo-systems. This article explains that Massive MIMO solutions or advanced antenna systems (AAS) with beamforming features comprises an AAS radio and Massive MIMO features such as beamforming which can be executed by algorithms in the AAS radio or a RAN Compute connected to the AAS radio or both. It further describes the use of channel estimation to understand multipath transmission delay and reshape beams in both time and frequency to modify the transmission power level of multiple OFDM tones:<br><br>"Of course, just being able to focus energy in a fixed direction is not very useful as people typically move around. So, to be able to control the direction and shape of the beams in any way we want in space, we also make the antennas individually controllable with their own radio chains, so we can change the amplitude and phase of their signals separately.<br><br>This gives us numerous coverage and capacity abilities, including:<br><br>• To create multiple beams at the same time<br>• To send and receive radio signals extremely quickly – on a fraction of a millisecond basis – where we want to, while reducing interference in directions |

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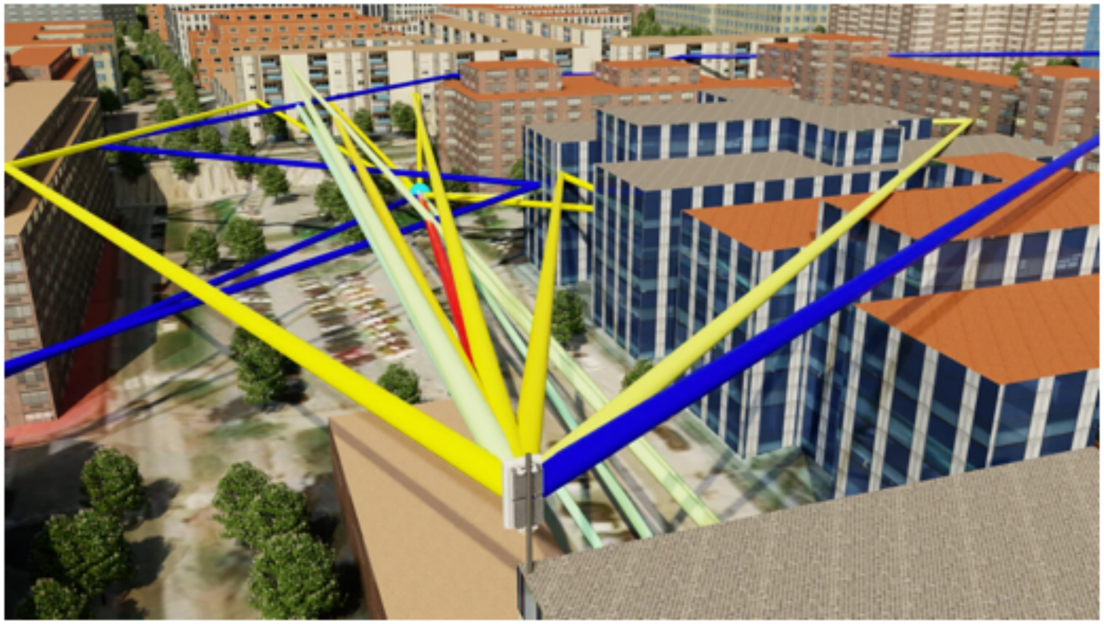
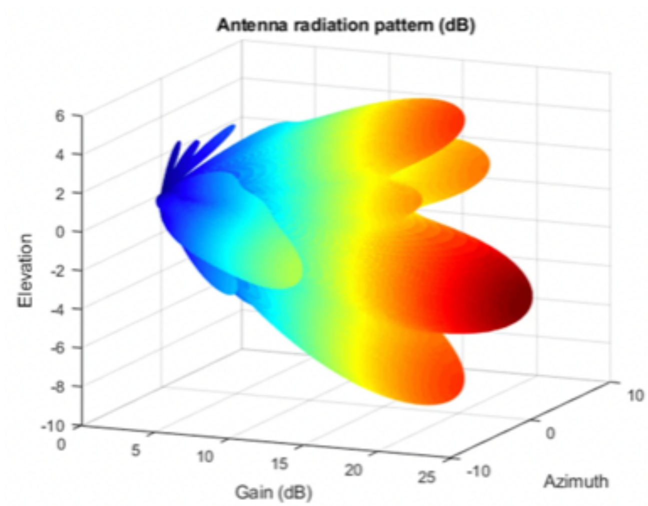
| | where we don´t want that energy to go or come from. All of this, for multiple users simultaneously!<br><br>But - this is no easy task. How do we "form" the right beams to get the most signal energy to the user that we want? People usually think of a beam as a simple concentration of energy that looks like the figure below. You just point it in the direction that you want and that´s all that you need. It is true that you can form beams like that, and they will often work quite well, but they are not always optimal.<br><br>The reason we can do better than a simple beam is that the "radio channel" is a highly complicated environment, since the signal path that travels between the base station and each device reflects off numerous objects causing standing waves and dips that change in time and in frequency at sub millisecond level, as multiple paths arrive at the receiver from all directions, as illustrated in the picture below.<br><br> |

Think of a choppy ocean… what should the ideal beams look like to navigate this environment with the best performance? To add to the complexity, this channel is different for each of the hundreds of moving devices that are connected within a cell so they each need precisely created beams of their own and of course when we send a beam to one user we don't want to interfere with others.

So, the beams must be highly precise, individual, and continually reshaped every fraction of a millisecond both in time and frequency, based on instant measurements of the radio channel across the spectrum together with large scale calculations to work out and apply the beams to the data we want to send or receive. The gigabits of data that are sent and received over the air interface are practically surfing the radio channel and just as in wave surfing, precise timing is essential to catch the radio waves. If you let your view of the channel information get too old, which happens extremely quickly, you will fall off the wave, and miss the chance to optimize your beamforming performance. The instantaneous beam that works best can look quite arbitrary as illustrated below but best achieves the goal of getting the energy exactly where we want until we change it for a new beam a fraction a millisecond later.



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| | For CSPs, the result is much greater coverage, much greater network capacity and high end-user speeds over a wider area compared to remote radio unit solutions. The CSP can exploit their valuable spectrum resources to the utmost without vastly increasing the number of sites. This has the benefit of reducing the cost per gigabit per area while preparing CSPs for future traffic growth - they can continue providing outstanding speeds and great coverage as the data traffic load gets heavier.<br><br>**The art and science behind Ericsson Advanced Antenna Systems**<br>We can clearly see the benefits of AAS. However, there are also challenges to realize its full potential:<br><br>• **Radio challenges:** Larger bandwidth and more antenna branches drive the need for increased processing capacity, which drives higher power consumption, size and weight at the base station.<br>• **Beamforming challenges:**<br>    • The radio environment changes on sub-millisecond timeframes as the smartphone moves. Adding to this complexity is of course the hundreds of other devices that connect within the cell.<br>    • The beams must be continually reshaped every fraction of a millisecond, based on instant snapshots of the channel, both in time and frequency.<br>    • To adapt the beams in a complex radio environment for many users simultaneously when using multiple antennas, requires millions of mathematical calculations per second<br><br>To address these challenges, Ericsson adds three key components: **access** to information about the instantaneous radio channel, clever **algorithms** which utilize this information, and the processing power of the Ericsson **silicon**. Fortunately, Ericsson's long experience in the AAS field has ensured that both our hardware design and beamforming algorithms are prepared for this.<br><br>The Ericsson Massive MIMO architecture has been designed to put as much as possible of the beamforming and MIMO processing in the AAS radio itself, close to the |

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| | antennas and radio channel, where we have **access** to real-time and fine granular information about the radio channel. Therefore, Ericsson is able to do channel estimation and beamforming weight calculations that follow the extremely rapid changes that occur on the radio channel almost instantaneously. You could say that Ericsson Massive MIMO antennas have a fingertip feel of the radio channel and can react to the real-time channel situation with the best possible beams.<br><br>Putting this processing in the radio where it belongs also has other advantages. The fronthaul bit rate from the radio to the RAN Compute is reduced, thus saving costs, and the RAN Compute can concentrate on its own tasks,- for example to schedule users over many cells, and to encode and decode the data bits on the user plane, which must be well protected before they are sent over the air.<br><br>Secondly, we need clever beamforming **algorithms** to act on the channel data. In fact, the way to do the beamforming in 5G is not defined by any 3GPP standard and is completely up to implementation, which means there is a lot of room for innovation and artistic freedom.<br><br>To solve the complex challenge of adapting to time-varying radio channel, we need to generate ultra-precise beamforming by applying different precoder weights to the antenna elements of our array so that after passing through the wireless channel to the target user, the signals from the multiple antennas add up coherently to boost the signal. This is analogous to creating a harmony in music by playing several tones on the piano at certain specific intervals so that when added up they form a pleasant-sounding chord.<br><br>But we simultaneously want to reduce interference to other users by having the signals from the different antenna elements add up destructively, akin to creating a dissonant-sounding chord in music by playing tones with other intervals (like a diminished fifth). The problem to generate optimal beamforming performance to achieve these goals simultaneously then becomes similar to composing a musical arrangement with complex harmonies and passages, while handling multiple instruments simultaneously, |

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| | both an art and a science! And as we know, it takes both skill and dedication to become a Mozart as it does to master the art of Massive MIMO.<br><br>To generate ultra-precise beamforming, a massive set of complex calculations needs to be performed in real-time, scaling with the number of antennas, the bandwidth and number of users. This adds up to millions of mathematical calculations per second, which requires an extreme processing capability. In addition, it also requires our sophisticated software features and algorithms to make sure that we leverage that hardware in the best way. This can only be achieved with Ericsson **silicon,** system on a chip (SoC) solution, as outlined in the previous blog. It can not only handle all that processing capacity inside the Massive MIMO radio, but also creates much tighter integration of components inside the radio. This way, we can build a high-performing radio without adding size, weight or energy consumption.<br><br>See, e.g., 3GPP TS 38.214 v 16.2.0 R16 (2020-07) (incorporated by reference herein)<br><br>§ 5.2.2.2 Precoding matrix indicator (PMI)<br><br>[describing Type I and Type II and Enhanced Type II Codebooks for MIMO beamforming precoding matrix]<br>…<br>5.2.2.2.1 Type I Single-Panel Codebook<br>…<br>5.2.2.2.2 Type I Multi-Panel Codebook<br>…<br>5.2.2.2.3 Type II Codebook<br>… |

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| | 5.2.2.2.4 Type II Port Selection Codebook<br>…<br>5.2.2.2.5 Enhanced Type II Codebook<br>…<br>5.2.2.2.6 Enhanced Type II Port Selection Codebook<br>…<br><br>See, e.g., Ziao Qin and Haifan Yin, A Review of Codebooks for CSI Feedback in 5G New Radio and Beyond, arXiv:2302.09222v2 13 Jun 2023<br><br>[describing Type I and Type II and Enhanced Type II Codebooks for MIMO beamforming precoding matrix]<br><br>Multiple-Input Multiple-Output (MIMO) has been an integral technology to improve system performance since 4G LTE R8 released in 2009. In 5G NR, this technology has evolved to massive MIMO [2] with an increasing scale of the antenna array. Massive MIMO provides higher transmission diversity, higher spatial multiplexing gain, and higher transmission directivity. Hence, higher spectral efficiency and more reliability can be achieved [3]. Particularly, the key to high transmission directivity brought by massive MIMO is beamforming, which enables multi-user spatial multiplexing. To achieve accurate beamforming, Channel State information (CSI) is the indispensable premise. At the base station (BS) side, the downlink (DL) CSI can be acquired by the feedback information from the users (UEs), i.e., CSI report [4]. Note that CSI report is more indispensable in frequency division duplex (FDD) mode than time division duplex (TDD) mode [5]. The reported CSI enables the BS to calculate the precoding matrix for |

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| | beamforming and user scheduling. In 3GPP standards, the CSI report process is achieved by the configuration of the codebook and the feedback of the codewords. At first, a codebook refers to a set of pre-defined precoders, a.k.a., codewords, and the UEs feed back the indices of the codewords to the base station. With the development of the standard nowadays, the meaning of codebook extends to the whole CSI report mechanism, which helps the base station compute the precoding matrix with the feedback from the UEs.<br><br>As another example, 5G NR beamforming technology is described in secondary sources, such as "MIMO Beamforming Using PMI Type II Precoding," Caroline Jenisha Ruth Mary Pramila Paul Sudhakar, Degree Project in Electrical Engineering, Second Cycle, Stockholm, Sweden 2021, KTH Royal Institute of Technology, available at https://www.diva-portal.org/smash/get/diva2:1618389/FULLTEXT01.pdf. This project lists Carolina Jenisha R P of KTH Royal Institute of Technology as Author with Ericsson AB as Host Company, Medhat Mohammad of Ericsson AB as Supervisor, and Ben Slimane of KTH Royal Institute of Technology as Examiner.<br><br>**2.2.1 Beamforming**<br><br>Focusing the power of all antenna elements combined with the help of beamformers or weights towards one direction is called beamforming as shown in figure 2.2.1. When the angular spread between the BS and UE is zero (i.e.) in the existence LOS or one dominant path the above definition applies. In reality, there exists multiple paths (i.e.) NLOS or multiple paths, which requires *precoding* at the transmitter or receiver. Precoder applies weights on to the antenna element that comprises of amplitude and phase for each antenna element. With the help of weights, the antenna can be electronically steered to radiate in the intended direction by suppressing the power in the other directions. Beamformers can be precoded to radiate in two or more propagating path making use of the diversity gain provided by the fading channel. In general, BF can be considered as a special case of precoding for LOS path. The precoded data is spatially combined and transmitted. |

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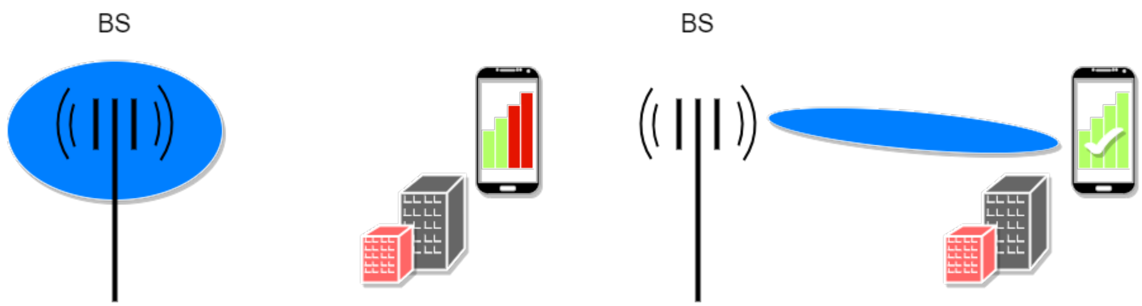
| | When BF is implemented at the the receiver added to BF at the transmitter provides<br><br>CHAPTER2. THEORETICAL CONCEPTS AND RELATED WORK<br><br><br><br><br>Figure 2.2.1: Compared to the BS with isotropic radiation (left) and BS that performs beamforming (right), the signal strenght of beamformed signal increases directivity towards the user which increases the received power thereby increasing the links data rate.<br><br>both array gain and diversity gain. As the number of antenna elements increases at the receiver, increases the average Signal to Noise Ratio (SNR) achieved by coherently combining all the antenna elements on the other hand diversity gain helps to increase the instantaneous SNR at the receiver by selective coherent combining of different antenna elements experiencing different fading pushing the combined SNR more concentrated towards the average SNR [11].<br><br>**2.2.2 Spatial Multiplexing**<br><br>The procedure beamforming when applied to different data streams can be spatially multiplexed in one time and frequency resource. The multipaths provided by MIMO is essentially used to improve the data rate of the UE. This can be visualised in two different scenarios as shown in figure 2.2.2. |

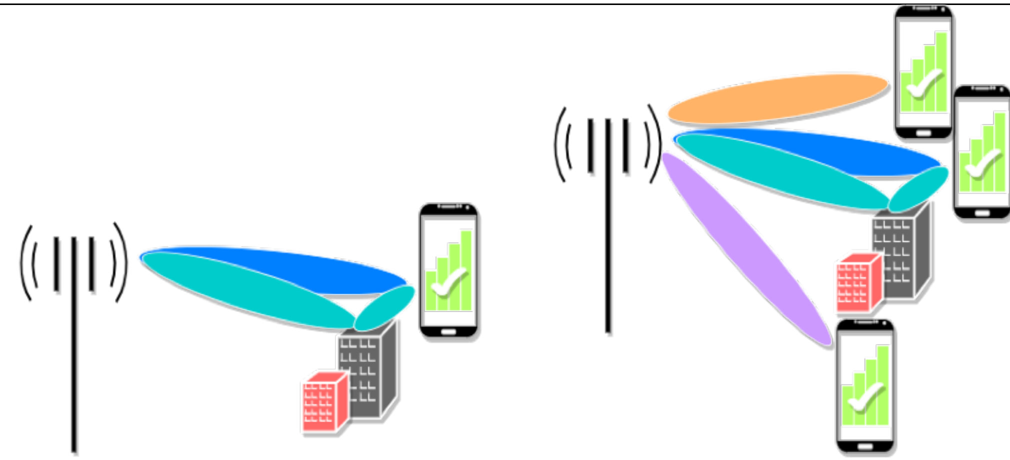


Figure 2.2.2: Spatial multiplexing seen in SUMIMO(left) and MUMIMO(right).

## 2.3 CSI reporting

The BS requires a pretext before transmitting data to the respective user. This pretext is referred to the information about channel observed from the direction of the user. CSI report is considered as a feedback from UE that carries the channel information which helps in designing the precoder or choosing the optimum precoder in case of codebook based precoding.

### 2.3.1 Beam Management

CSI acquisition is done in two stages. The first stage is Beam Management (BM) where the UE measures the Reference Signal Received Power (RSRP) of the set of analog beams transmitted by the BS and reports the beam ID of the best beam to the BS [9]. NR DL measurements for BM include Synchronization Signals (SS) bursts and Channel State InformationReference Signals (CSIRS) or NR Uplink (UL) measurements for BM

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| | include Sounding Reference Signals (SRS) as shown in figure 2.3.1. In BM based CSIRS, a set of analog beams is sent by BS to UE and the UE reports the CSI to the BS [8]. On the other hand, in BM based SRS, channel measurements are sent by the UE via a set of analog beams and received by BS. BS selects the best analog beams after measurements based on channel reciprocity where angle of arrival becomes the angle of departure of analog beams [8]. This holds, for instance, if the UE has the ability to transmit and receive with the same number of antennas as in Time Division Duplexing (TDD) [9]. However, UEs may use a different number of antennas for transmission and reception where channel reciprocity could not be met. Additionally, SRS based BM is more suitable for linear precoders as the precoder matrix requires detailed CSI whereas CSI-RS based BM is more suitable for GoB precoders. According to 5G standardization, BM in general consists of beam sweeping, beam measurement, beam determination, beam reporting , beam maintenance and beam recovery [8, 9]. These procedures are repeated to update the links periodically.<br><br>**2.3.2 PMI report**<br><br>The first stage is followed by the second stage, namely CSI acquisition report from the UE. After the NR DL or UL BM measurements, the BS assigns a subset of analog beams towards that UEs location and the UE generates the CSI report and sends the report to the BS [8]. The CSI report contains, |

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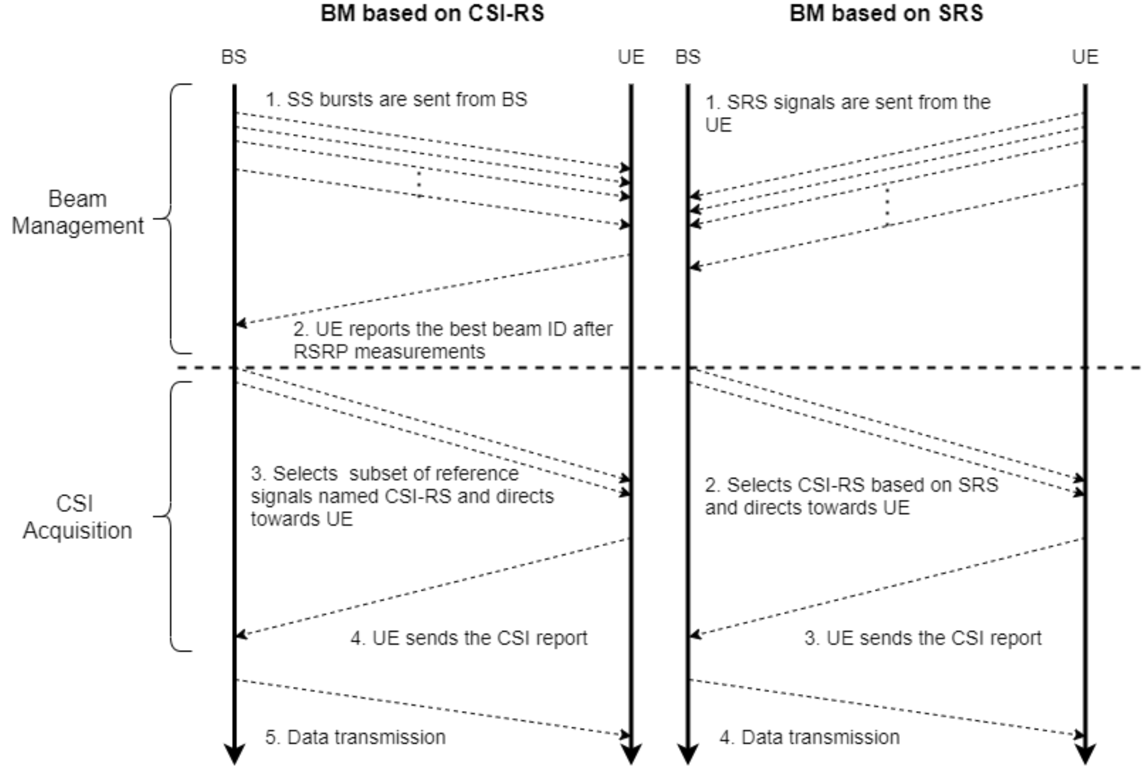
| |  <br>Figure 2.3.1: Beam Management procedures<br><br>• *Rank Indicator (RI)*, used to indicate the preferred number of transmission layers.<br><br>• *Precoder Matrix Indicator (PMI)*, used to indicate preferred design of precoder matrix for the given rank.<br><br>• *Channel Quality Indicator (CQI)*, used to indicate the suitable channelcoding rate and modulation scheme for the given PMI. [2]. |

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| | The PMI values corresponding to the different precoder matrix is chosen from the precoder codebook defined by the standards . Despite the CSI report sent by the UE, the network can choose any precoder matrix design for data transmission. Although choosing the precoder design preferred by UE makes sense, in many cases that is not entirely possible especially in MUMIMO [10]. Therefore, NR defines two different types of CSI that differ in size and structure of the precoder matrix. *Type I CSI* (standard/low resolution) is predominantly used for SUMIMO scenarios as it relies on the UE to suppress the interference due to the different layers. This is due to the fact that the number of layers will never be larger than the number of receiver antennas. On the other hand, *Type II CSI* (high resolution) is primarily used for MUMIMO and is limited to a smaller number of layers (maximum of two). Since the number of received streams is larger than the number of receiver antennas, the interference is managed by the BS with the help of BF or precoder design [9].<br><br>See also "Chapter 3: Methodologies," which is incorporated by reference herein.<br><br>5G NR beamforming is also described in secondary sources, such as Ziao Qin and Haifan Yin, "A Review of Codebooks for CSI Feedback in 5G New Radio and Beyond," submitted, February 2023, 10.48550/arXiv.2302.09222, available online: https://arxiv.org/abs/2302.09222, also available at https://www.researchgate.net/publication/368665066_A_Review_of_Codebooks_for_CSI_Feedback_in_5G_New_Radio_and_Beyond<br><br>5G NR beamforming is also described in secondary sources, such as on the NR Cell Performance Evaluation with MIMO page on https://www.mathworks.com/help/5g/ug/nr-cell-performance-evaluation-with-mimo.html. |

## Claim 28

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| 28. The method as recited in claim 13, further comprising: using at least one transmitting device transmit antenna operatively coupled to said transmitting device to transmit said modified forward path data signal over at least one forward transmission path to the receiving device. | The Accused Products/Instrumentalities perform the method recited in claim 13, further comprising: using at least one transmitting device transmit antenna operatively coupled to said transmitting device to transmit said modified forward path data signal over at least one forward transmission path to the receiving device. The base station uses its antenna array to transmit the precoded modified forward path data signal over at least one forward transmission path to the receiving device. See claim 1 and evidence cited therein.<br><br>For example, the Ericsson or Nokia base station includes an antenna array coupled to the base station to wirelessly receive the exemplary reverse path data signals described for claim 1 over at least one reverse transmission path from the receiving device. The base station antenna array also has transmit antenna to transmit the modified forward path data signal (beamformed precoded downlink transmission signal) over at least one forward transmission path to the receiving device (the user equipment). The use of transmit antenna are illustrated in the Ericsson and Nokia documentation shown in claim 1[pre]-1[a].<br><br>See https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks (also available at https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks) (illustrating Ericsson base stations)<br><br>***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell. |

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| | DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short- term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics. |

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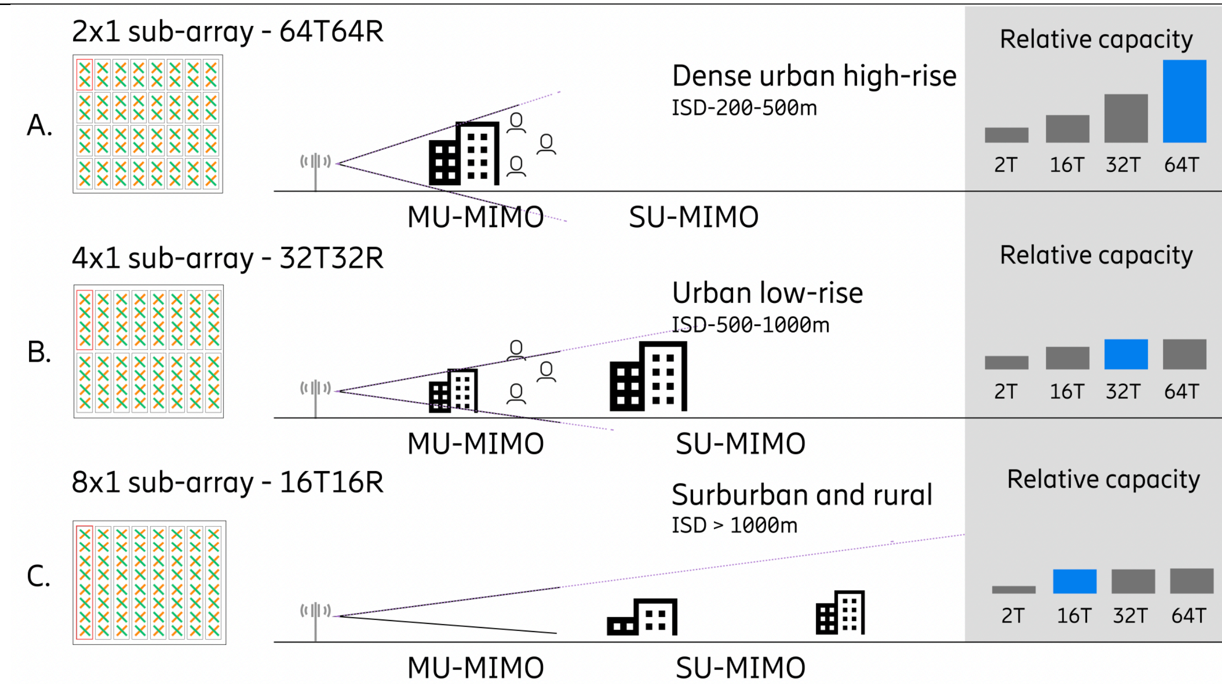
| | <br>See https://www.nokia.com/networks/mobile-networks/airscale-radio-access/ (illustrating Nokia base stations)<br>See e.g. 3GPP TS 38.300 v17.2.0, § 4.1. |

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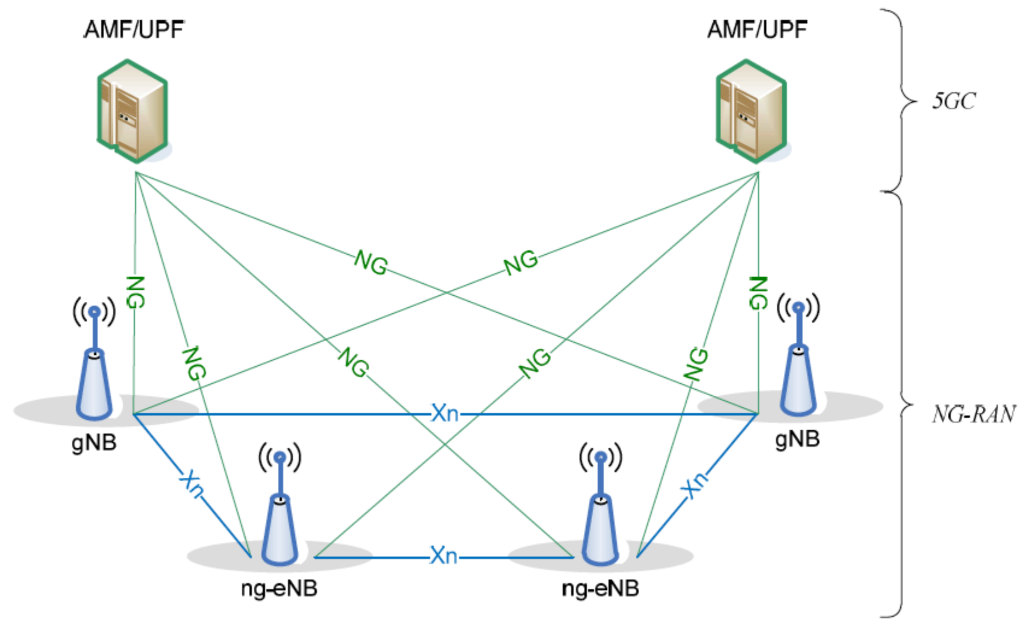
| | The NG-RAN architecture is illustrated in Figure 4.1-1 below.   **Figure 4.1-1: Overall Architecture** |

## Claim 32

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| 32. The method as recited in claim 28, further comprising: setting at least one antenna pointing parameter associated with said at least one transmitting device transmit antenna based on said at least one forward path pre-equalization parameter. | The Accused Products/Instrumentalities perform the method recited in claim 28, further comprising: setting at least one antenna pointing parameter associated with said at least one transmitting device transmit antenna based on said at least one forward path pre-equalization parameter. For example, in the TDD example described for claim 1, a forward path pre-equalization parameter (e.g., precoding / beamforming coefficients) is used to set at least one antenna pointing parameter associated with the Ericsson or Nokia base station transmit antenna. As another example, in the FDD example described for claim 1, a forward path pre-equalization parameter (e.g., precoding / beamforming coefficients) is used to set at least one antenna pointing parameter associated with the Ericsson or Nokia base station transmit antenna. See claim 1 and evidence cited therein.<br><br>For example, the 5G MIMO Nokia and Ericsson base station transmitting devices apply beamforming coefficients and precoding for downlink transmissions ("forward path pre-equalization parameter") to point beams in certain directions which corresponds to setting antenna pointing parameter associated with transmit antenna based on forward path pre-equalization parameter. The beamforming coefficients result in directed transmissions from the antenna that are pointed in specified directions.<br><br>See, e.g., Ericsson Advanced Antenna System for 5G Networks white paper / https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks:<br><br>***Key terms***<br>**AAS radio** = Hardware unit that comprises an antenna array, radio chains and parts of the baseband, all tightly integrated to facilitate AAS features<br>**AAS feature** = A multi-antenna feature (such as beamforming and MIMO) that can be executed in the AAS radio, in the baseband unit or both<br>**AAS** = AAS radio + AAS features<br>**Conventional system** = Passive antenna + remote radio unit comprising a low number (2, 4 or 8) of radio chains<br>**Dual-polarized antenna element** = Combination of two antenna elements with orthogonal polarizations with the purpose of enabling diversity and doubling the number of antenna elements on a given physical area |

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| | **What is an advanced antenna system?**<br>An advanced antenna system (AAS) is a combination of an AAS radio and a set of AAS features. An AAS radio consists of an antenna array closely integrated with the hardware and software required for transmission and reception of radio signals, and signal processing algorithms to support the execution of the AAS features. Compared to conventional systems, this solution provides much greater adaptivity and steerability, in terms of adapting the antenna radiation patterns to rapidly time-varying traffic and multi-path radio propagation conditions. In addition, multiple signals may be simultaneously received or transmitted with different radiation patterns.<br><br>***Multi-antenna techniques***<br>Multi-antenna techniques, here referred to as AAS features, include beamforming and MIMO. Such features are already used with conventional systems in today's LTE networks. Applying AAS features to an AAS radio results in significant performance gains because of the higher degrees of freedom provided by the larger number of radio chains, also referred to as Massive MIMO.<br><br>**Beamforming**<br>When transmitting, beamforming is the ability to direct radio energy through the radio channel toward a specific receiver, as shown in the top left quadrant of **Figure 1**. By adjusting the phase and amplitude of the transmitted signals, constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput. Similarly, when receiving, beamforming is the ability to collect the signal energy from a specific transmitter. The beams formed by an AAS are constantly adapted to the surroundings to give high performance in both UL and DL.” |

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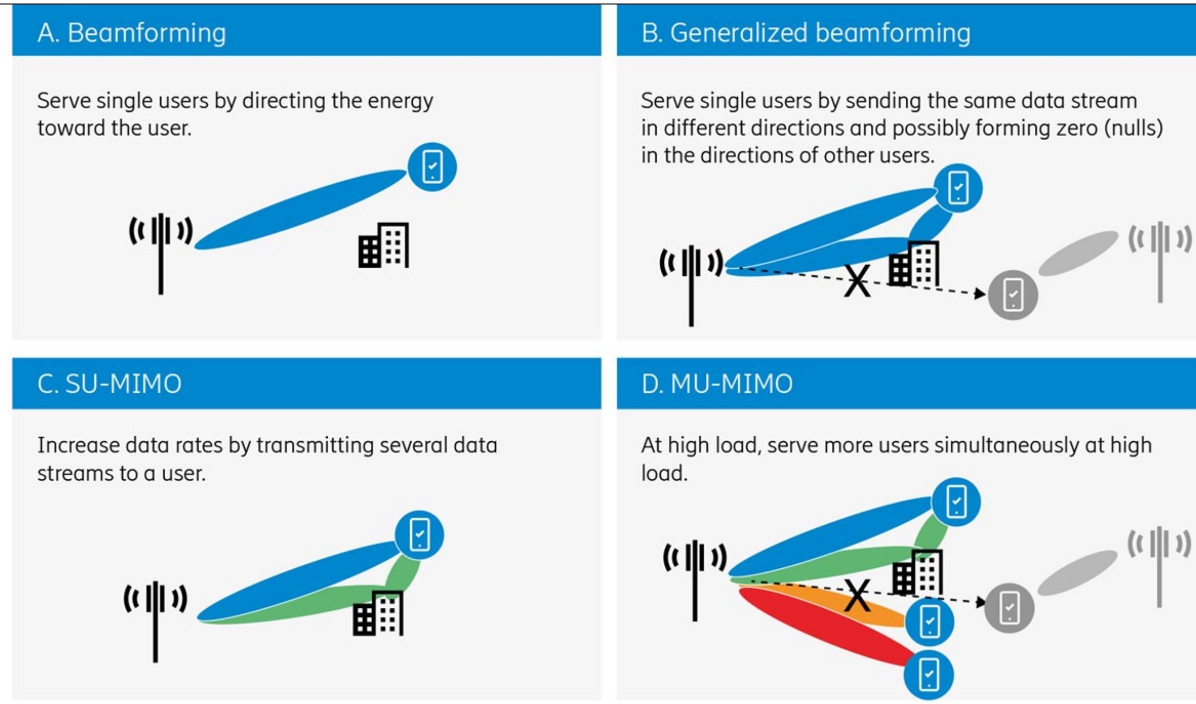
| | <br>Figure 1: Beamforming and MIMO, with the different colors of the filled beams representing streams.<br><br>Although often very effective, transmitting energy in only one direction does not always provide an optimum solution. In multi-path scenarios, where the radio channel comprises multiple propagation paths from transmitter to receiver through diffraction around corners and reflections against buildings or other objects, it is beneficial to send the same data stream in several different paths (direction and/or polarization) with phases and amplitudes controlled in a way that they add constructively at the receiver [5]. This is referred to as generalized beamforming, as shown in the upper right quadrant of Figure 1. As part of generalized beamforming, it is also possible to reduce interference to other UEs, which is known as null forming. This is achieved by |

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| | controlling the transmitted signals in a way that they cancel each other out at the interfered UEs.<br><br>**MIMO (Multiple Input, Multiple Output) techniques**<br>Spatial multiplexing, here referred to as MIMO, is the ability to transmit multiple data streams, using the same time and frequency resource, where each data stream can be beamformed. The purpose of MIMO is to increase throughput. MIMO builds on the basic principle that when the received signal quality is high, it is better to receive multiple streams of data with reduced power per stream, than one stream with full power. The potential is large when the received signal quality is high and the streams do not interfere with each other. The potential diminishes when the mutual interference between streams increases. MIMO works in both UL and DL, but for simplicity the description below will be based on the DL.<br><br>Single-user MIMO (SU-MIMO) is the ability to transmit one or multiple data streams, called layers, from one transmitting array to a single user. SU-MIMO can thereby increase the throughput for that user and increase the capacity of the network. The number of layers that can be supported, called the rank, depends on the radio channel. To distinguish between DL layers, a UE needs to have at least as many receiver antennas as there are layers.<br><br>SU-MIMO can be achieved by sending different layers on different polarizations in the same direction. SU-MIMO can also be achieved in a multi path environment, where there are many radio propagation paths of similar strength between the AAS and the UE, by sending different layers on different propagation paths, as shown in the bottom left quadrant of Figure 1.<br><br>In multi-user MIMO (MU-MIMO), which is shown in the bottom right quadrant of Figure 1, the AAS simultaneously sends different layers in separate beams to different users using the same time and frequency resource, thereby increasing the network capacity. In order to use MU-MIMO, the system needs to find two or more users that need to transmit or receive data at the very same time. Also, for efficient MU-MIMO, the |

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| | interference between the users should be kept low. This can be achieved by using generalized beamforming with null forming such that when a layer is sent to one user, nulls are formed in the directions of the other simultaneous users.<br><br>The achievable capacity gains from MU-MIMO depend on receiving each layer with good signal-to-interference-and-noise-ratio (SINR). As with SU-MIMO, the total DL power is shared between the different layers, and therefore the power (and thus SINR) for each user is reduced as the number of simultaneous MU-MIMO users increases. Also, as the number of users grows, the SINR will further deteriorate due to mutual interference between the users. Therefore, the network capacity typically improves as the number of MIMO layers increases, to a point at which power sharing and interference between users result in diminishing gains, and eventually also losses.<br><br>It should be noted that the practical benefits of many layers in MU-MIMO are limited by the fact that, in today's real networks, even with a high number of simultaneous connected users, there tends not to be many users who want to receive data simultaneously. This is due to the bursty (chatty) nature of data transmission to most users. Since the AAS and the transport network must be dimensioned for the maximum number of layers, the MNO needs to consider how many layers are required in their networks. In typical MBB deployments with the current 64T64R AAS variants, the vast majority of the DL and UL capacity gains can be achieved with up to 8 layers."<br><br>***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine |

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| | how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.<br><br>DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short- term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics.<br><br>The suitable channel knowledge scheme to use depends on UL coverage and UE capabilities. In cases where UL coverage is limiting, UE feedback offers a more robust |

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| | operation, whereas full UL channel estimation is applicable in scenarios with good coverage. In short, both reciprocity and UE feedback-based beamforming are needed.<br><br>**Antenna array structure**<br>The purpose of using a rectangular antenna array, as shown in section A of Figure 2, is to enable high-gain beams and make it possible to steer those beams over a range of angles. The gain is achieved, in both UL and DL, by constructively combining signals from a number of antenna elements. The more antenna elements there are, the higher the gain. Steerability is achieved by individually controlling the amplitude and phase of smaller parts of the antenna array. This is usually done by dividing the antenna array into so called sub-arrays (groups of non-overlapping elements), as shown in section C of Figure 2, and by applying two dedicated radio chains per sub-array (one per polarization) to enable control, as shown in section D. In this way it is possible to control the direction and other properties of the created antenna array beam<br><br>https://www.ericsson.com/4917a1/assets/local/reports-papers/ericsson-technology-review/docs/2022/the-role-of-massive-mimo-in-5g-networks.pdf<br><br>**Multi-antenna technologies**<br><br>Massive MIMO improves network coverage and capacity through the use of the three multi-antenna technologies – beamforming, null forming and spatial multiplexing – shown in *Figure 1*. All three are applicable to both the downlink (DL) and the uplink (UL). The purpose of beamforming is to amplify transmitted/received signals more in some directions than others. The goal is to achieve a high beamforming gain in the direction of the device of interest to improve link quality in terms of signal-to-interference-plus-noise-ratio (SINR). This translates into higher spectral efficiency and/or better coverage for a single link, which in turn results in better network coverage, capacity and user throughput.<br><br>https://www.sharetechnote.com/html/5G/5G_SRS.html<br><br>**Phase I** - RRC Configuration for SRS<br>This is the phase where gNB determines about SRS configuration (e.g., SRS physical resources, usage, report period timing etc.) and notifies the configuration to UE via RRC messages (e.g., RRCSetup, RRCReconfiguration). |

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| | **Phase II** - SRS transmission from UE:<br>In this phase, the UE transmits the SRS, which is a predefined signal with known characteristics, at a specific time and frequency. The SRS configuration is provided to the UE by the gNB, and it may vary depending on the cell's conditions and traffic requirements. The UE sends the SRS periodically or aperiodically, as instructed by the gNB, on the uplink (UL) channel.<br>**NOTE** : gNB can configure UE to transmit the srs across the full band at once or can configure UE to transmit the srs for a certain segment of the frequency band using the parameter explained in Bandwidth Configuration.<br>**NOTE** : gNB configures how often and at which timing UE should send SRS. gNB would get better and more accurate information as it let UE to transmit more often for wider frequency span, but overhead caused by srs transmission would get higher.<br>**Phase III** - SRS reception at gNB and Analysis:<br>Upon receiving the SRS from the UE, the gNB measures and analyzes the received signal. It estimates the channel state information (CSI) by comparing the received SRS with the known reference signal. The gNB evaluates various parameters, such as the path loss, propagation delay(phase delay), and received signal strength, to understand the current radio environment and channel conditions between the gNB and the UE.<br><br>https://telcomaglobal.com/p/5g-nr-srs-sounding-reference-signals<br><br>**5G NR SRS (Sounding Reference Signals)**<br>Introduction<br>SRS is Sounding Reference Signal is a reference signal transmitted by the UE in the uplink direction which is used by the eNodeB to estimate the uplink channel quality over a wider bandwidth. SRS is a UL reference signal which is transmitted by UE to the base station. SRS gives information about the combined effect of multipath fading, scattering, Doppler, and power loss of the transmitted signal. Sounding reference signals are uplink physical signals employed by user equipment (UE) for uplink channel sounding, including channel quality estimation and synchronization. Unlike Demodulation reference signals (DM-RS), SRS is not associated with any physical uplink channels, and they support uplink channel-dependent scheduling and link adaptation. SRS assist in:<br>• Codebook-based closed-loop spatial multiplexing<br>• Control uplink transmit timing<br>• Reciprocity-based downlink precoding in multi-user MIMO setups<br>• Quasi co-location of physical channels and reference signals |

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| | In 5G NR, the SRS is transmitted by the UE for uplink channel sounding, which includes channel estimation and synchronization. An NR-SRS is an uplink orthogonal frequency division multiplexing (OFDM) signal filled with a Zadoff-Chu sequence on different subcarriers. For the purposes of communications, the SRS is used for closed-loop spatial multiplexing, uplink transmitting timing control, and reciprocity multi-user downlink precoding. To utilize the channel sounding function, the SRS must be known by both the UE and the gNB. UE act as a mobile transmitter and gNB act as a base station receiver.<br><br>Base station estimates the channel quality using this reference signal and manages further resource scheduling, Beam management, and power control of the signal. So SRS provides information to gNB about the channel over the full bandwidth and using this information, gNB takes decisions for resource allocation which has better channel quality as compared to other Bandwidth regions<br><br>https://www.mathworks.com/help/5g/ug/tdd-reciprocity-based-pdsch-beamforming-using-srs.html<br><br>**TDD Reciprocity-Based PDSCH MU-MIMO Using SRS**<br><br>This example implements downlink multiuser multiple-input multiple-output (MU-MIMO) by exploiting channel reciprocity in a time division duplex (TDD) scenario. The example shows how to determine beamforming weights for physical downlink shared channel (PDSCH) transmission by using channel estimates based on uplink sounding reference signals (SRS) transmitted for each user, and how to schedule PDSCHs for multiple users in the same time and frequency resources.<br><br>Introduction<br><br>TDD systems use the same frequency band for uplink (UL) and downlink (DL) transmissions. The radio channel is reciprocal because it has the same characteristics in both UL and DL directions. Exploiting this reciprocity, you can use a UL transmission to obtain a channel estimate and then use this channel estimate to calculate parameters, including beamforming, for a DL transmission. This method is known as reciprocity-based beamforming.<br><br>This example implements downlink MU-MIMO by calculating a channel estimate for multiple users based on their SRS transmissions. Assuming reciprocity, the example then uses these channel estimates to select a set of users to be scheduled for PDSCH transmission and calculates DL beamforming weights for PDSCH transmissions to those users. When the base station has a |

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| | sufficient number of antennas, it is possible to beamform PDSCH transmissions for a set of users in the same time and frequency resources such that the users suffer little interference from each other.<br><br>This example schedules SRS transmissions for all UEs in the UL part of the special slot, and schedules PDSCH transmissions for UEs chosen by the user selection algorithm in DL slots and the DL part of special slots<br><br>For example, Ericsson published “How to build high-performing Massive MIMO systems,” Billy Hogan, Bo Göransson, Sebastian Faxér, Sibel Tombaz, available athttps://www.ericsson.com/en/blog/2021/2/how-to-build-high-performing-massive-mimo-systems. This article explains that Massive MIMO solutions or advanced antenna systems (AAS) with beamforming features comprises an AAS radio and Massive MIMO features such as beamforming which can be executed by algorithms in the AAS radio or a RAN Compute connected to the AAS radio or both. It further describes the use of channel estimation to understand multipath transmission delay and reshape beams in both time and frequency to modify the transmission power level of multiple OFDM tones:<br><br>“Of course, just being able to focus energy in a fixed direction is not very useful as people typically move around. So, to be able to control the direction and shape of the beams in any way we want in space, we also make the antennas individually controllable with their own radio chains, so we can change the amplitude and phase of their signals separately.<br><br>This gives us numerous coverage and capacity abilities, including:<br><br>• To create multiple beams at the same time<br>• To send and receive radio signals extremely quickly – on a fraction of a millisecond basis – where we want to, while reducing interference in directions where we don´t want that energy to go or come from. All of this, for multiple users simultaneously!<br><br>But - this is no easy task. How do we “form” the right beams to get the most signal energy to the user that we want? People usually think of a beam as a simple concentration of energy that looks like the figure below. You just point it in the direction |

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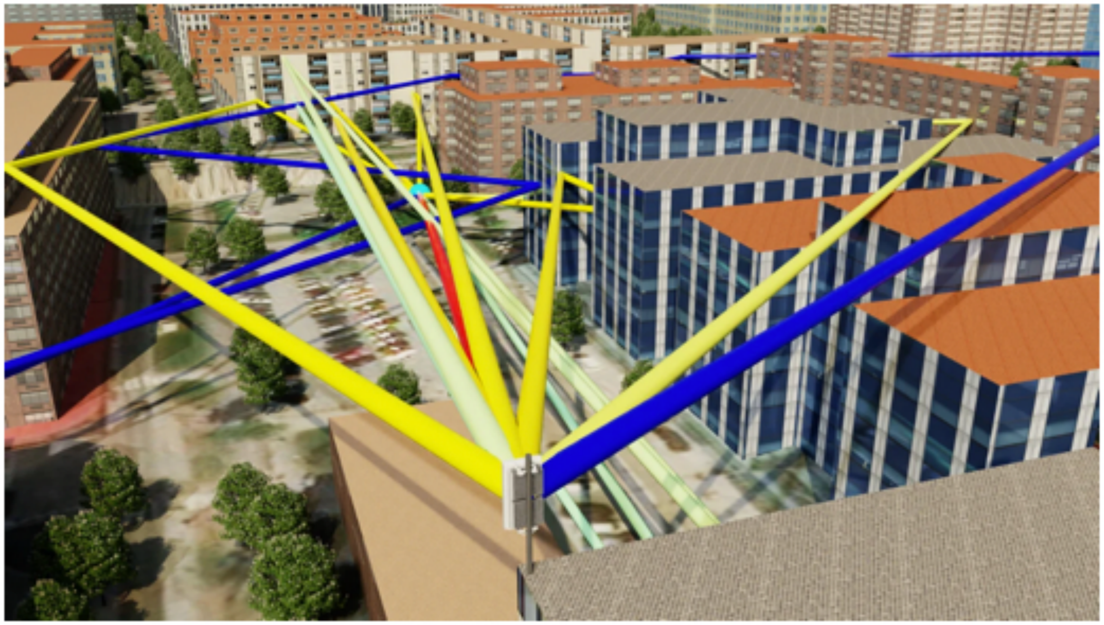
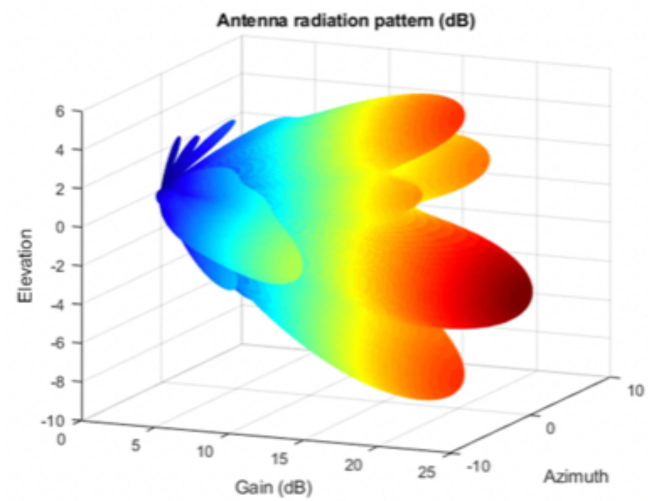
| | that you want and that´s all that you need. It is true that you can form beams like that, and they will often work quite well, but they are not always optimal.<br><br>The reason we can do better than a simple beam is that the “radio channel” is a highly complicated environment, since the signal path that travels between the base station and each device reflects off numerous objects causing standing waves and dips that change in time and in frequency at sub millisecond level, as multiple paths arrive at the receiver from all directions, as illustrated in the picture below.<br><br><br><br>Think of a choppy ocean… what should the ideal beams look like to navigate this environment with the best performance? To add to the complexity, this channel is different for each of the hundreds of moving devices that are connected within a cell so they each need precisely created beams of their own and of course when we send a beam to one user we don’t want to interfere with others. |

So, the beams must be highly precise, individual, and continually reshaped every fraction of a millisecond both in time and frequency, based on instant measurements of the radio channel across the spectrum together with large scale calculations to work out and apply the beams to the data we want to send or receive. The gigabits of data that are sent and received over the air interface are practically surfing the radio channel and just as in wave surfing, precise timing is essential to catch the radio waves. If you let your view of the channel information get too old, which happens extremely quickly, you will fall off the wave, and miss the chance to optimize your beamforming performance. The instantaneous beam that works best can look quite arbitrary as illustrated below but best achieves the goal of getting the energy exactly where we want until we change it for a new beam a fraction a millisecond later.




For CSPs, the result is much greater coverage, much greater network capacity and high end-user speeds over a wider area compared to remote radio unit solutions. The CSP can exploit their valuable spectrum resources to the utmost without vastly increasing the number of sites. This has the benefit of reducing the cost per gigabit per

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| | area while preparing CSPs for future traffic growth - they can continue providing outstanding speeds and great coverage as the data traffic load gets heavier.<br><br>**The art and science behind Ericsson Advanced Antenna Systems**<br>We can clearly see the benefits of AAS. However, there are also challenges to realize its full potential:<br><br>• **Radio challenges:** Larger bandwidth and more antenna branches drive the need for increased processing capacity, which drives higher power consumption, size and weight at the base station.<br>• **Beamforming challenges:**<br>    • The radio environment changes on sub-millisecond timeframes as the smartphone moves. Adding to this complexity is of course the hundreds of other devices that connect within the cell.<br>    • The beams must be continually reshaped every fraction of a millisecond, based on instant snapshots of the channel, both in time and frequency.<br>    • To adapt the beams in a complex radio environment for many users simultaneously when using multiple antennas, requires millions of mathematical calculations per second<br><br>To address these challenges, Ericsson adds three key components: **access** to information about the instantaneous radio channel, clever **algorithms** which utilize this information, and the processing power of the Ericsson **silicon**. Fortunately, Ericsson's long experience in the AAS field has ensured that both our hardware design and beamforming algorithms are prepared for this.<br><br>The Ericsson Massive MIMO architecture has been designed to put as much as possible of the beamforming and MIMO processing in the AAS radio itself, close to the antennas and radio channel, where we have **access** to real-time and fine granular information about the radio channel. Therefore, Ericsson is able to do channel estimation and beamforming weight calculations that follow the extremely rapid changes that occur on the radio channel almost instantaneously. You could say that |

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| | Ericsson Massive MIMO antennas have a fingertip feel of the radio channel and can react to the real-time channel situation with the best possible beams.<br><br>Putting this processing in the radio where it belongs also has other advantages. The fronthaul bit rate from the radio to the RAN Compute is reduced, thus saving costs, and the RAN Compute can concentrate on its own tasks,- for example to schedule users over many cells, and to encode and decode the data bits on the user plane, which must be well protected before they are sent over the air.<br><br>Secondly, we need clever beamforming **algorithms** to act on the channel data. In fact, the way to do the beamforming in 5G is not defined by any 3GPP standard and is completely up to implementation, which means there is a lot of room for innovation and artistic freedom.<br><br>To solve the complex challenge of adapting to time-varying radio channel, we need to generate ultra-precise beamforming by applying different precoder weights to the antenna elements of our array so that after passing through the wireless channel to the target user, the signals from the multiple antennas add up coherently to boost the signal. This is analogous to creating a harmony in music by playing several tones on the piano at certain specific intervals so that when added up they form a pleasant-sounding chord.<br><br>But we simultaneously want to reduce interference to other users by having the signals from the different antenna elements add up destructively, akin to creating a dissonant-sounding chord in music by playing tones with other intervals (like a diminished fifth). The problem to generate optimal beamforming performance to achieve these goals simultaneously then becomes similar to composing a musical arrangement with complex harmonies and passages, while handling multiple instruments simultaneously, both an art and a science! And as we know, it takes both skill and dedication to become a Mozart as it does to master the art of Massive MIMO. |

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| | To generate ultra-precise beamforming, a massive set of complex calculations needs to be performed in real-time, scaling with the number of antennas, the bandwidth and number of users. This adds up to millions of mathematical calculations per second, which requires an extreme processing capability. In addition, it also requires our sophisticated software features and algorithms to make sure that we leverage that hardware in the best way. This can only be achieved with Ericsson **silicon,** system on a chip (SoC) solution, as outlined in the previous blog. It can not only handle all that processing capacity inside the Massive MIMO radio, but also creates much tighter integration of components inside the radio. This way, we can build a high-performing radio without adding size, weight or energy consumption. |

## Claim 33

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| 33. The method as recited in claim 28, further comprising: setting at least one phased array antenna transmission directing parameter associated with said at least one transmitting device transmit antenna based on said at least one forward path pre-equalization parameter. | The Accused Products/Instrumentalities perform the method recited in claim 28, further comprising: setting at least one phased array antenna transmission directing parameter associated with said at least one transmitting device transmit antenna based on said at least one forward path pre-equalization parameter. For example, in the TDD example described for claim 1, a forward path pre-equalization parameter (e.g., precoding / beamforming coefficients) is used to set at least one phased array antenna transmission directing parameter associated with the Ericsson or Nokia base station transmit antenna. As another example, in the FDD example described for claim 1, a forward path pre-equalization parameter (e.g., precoding / beamforming coefficients) is used to set at least one phased array antenna transmission directing parameter associated with the Ericsson or Nokia base station transmit antenna. The Ericsson AAS radio base station or Nokia 5G base station includes phased array antenna and the precoding / beamforming coefficients set phased array antenna transmission directing parameter to generate spatial beams. See claim 1 and evidence cited therein.<br><br>For example, the 5G MIMO Nokia and Ericsson base station transmitting devices apply beamforming coefficients and precoding for downlink transmissions ("forward path pre-equalization parameter") to point beams in certain directions which corresponds to setting phased array antenna transmission directing parameter associated with transmit antenna based on forward path pre-equalization parameter. The beamforming coefficients result in directed transmissions from the antenna that are pointed in specified directions.<br><br>See, e.g., Ericsson Advanced Antenna System for 5G Networks white paper / https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks:<br><br>***Key terms***<br>**AAS radio** = Hardware unit that comprises an antenna array, radio chains and parts of the baseband, all tightly integrated to facilitate AAS features<br>**AAS feature** = A multi-antenna feature (such as beamforming and MIMO) that can be executed in the AAS radio, in the baseband unit or both<br>**AAS** = AAS radio + AAS features<br>**Conventional system** = Passive antenna + remote radio unit comprising a low number (2, 4 or 8) of radio chains<br>**Dual-polarized antenna element** = Combination of two antenna elements |

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| | with orthogonal polarizations with the purpose of enabling diversity and doubling the number of antenna elements on a given physical area<br><br>**What is an advanced antenna system?**<br>An advanced antenna system (AAS) is a combination of an AAS radio and a set of AAS features. An AAS radio consists of an antenna array closely integrated with the hardware and software required for transmission and reception of radio signals, and signal processing algorithms to support the execution of the AAS features. Compared to conventional systems, this solution provides much greater adaptivity and steerability, in terms of adapting the antenna radiation patterns to rapidly time-varying traffic and multi-path radio propagation conditions. In addition, multiple signals may be simultaneously received or transmitted with different radiation patterns.<br><br>***Multi-antenna techniques***<br>Multi-antenna techniques, here referred to as AAS features, include beamforming and MIMO. Such features are already used with conventional systems in today's LTE networks. Applying AAS features to an AAS radio results in significant performance gains because of the higher degrees of freedom provided by the larger number of radio chains, also referred to as Massive MIMO.<br><br>**Beamforming**<br>When transmitting, beamforming is the ability to direct radio energy through the radio channel toward a specific receiver, as shown in the top left quadrant of **Figure 1**. By adjusting the phase and amplitude of the transmitted signals, constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput. Similarly, when receiving, beamforming is the ability to collect the signal energy from a specific transmitter. The beams formed by an AAS are constantly adapted to the surroundings to give high performance in both UL and DL.” |

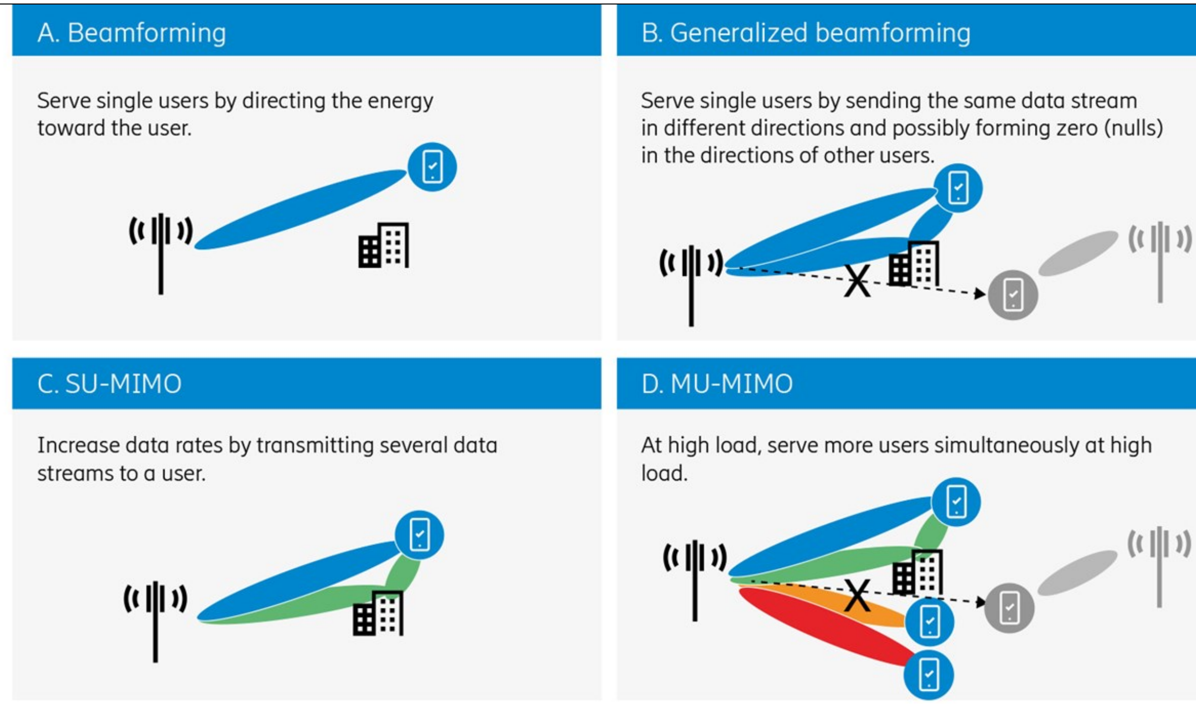


Figure 1: Beamforming and MIMO, with the different colors of the filled beams representing streams.

Although often very effective, transmitting energy in only one direction does not always provide an optimum solution. In multi-path scenarios, where the radio channel comprises multiple propagation paths from transmitter to receiver through diffraction around corners and reflections against buildings or other objects, it is beneficial to send the same data stream in several different paths (direction and/or polarization) with phases and amplitudes controlled in a way that they add constructively at the receiver [5]. This is referred to as generalized beamforming, as shown in the upper right quadrant of Figure 1. As part of generalized beamforming, it is also possible to reduce interference to other UEs, which is known as null forming. This is achieved by

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| | controlling the transmitted signals in a way that they cancel each other out at the interfered UEs.<br><br>**MIMO (Multiple Input, Multiple Output) techniques**<br>Spatial multiplexing, here referred to as MIMO, is the ability to transmit multiple data streams, using the same time and frequency resource, where each data stream can be beamformed. The purpose of MIMO is to increase throughput. MIMO builds on the basic principle that when the received signal quality is high, it is better to receive multiple streams of data with reduced power per stream, than one stream with full power. The potential is large when the received signal quality is high and the streams do not interfere with each other. The potential diminishes when the mutual interference between streams increases. MIMO works in both UL and DL, but for simplicity the description below will be based on the DL.<br><br>Single-user MIMO (SU-MIMO) is the ability to transmit one or multiple data streams, called layers, from one transmitting array to a single user. SU-MIMO can thereby increase the throughput for that user and increase the capacity of the network. The number of layers that can be supported, called the rank, depends on the radio channel. To distinguish between DL layers, a UE needs to have at least as many receiver antennas as there are layers.<br><br>SU-MIMO can be achieved by sending different layers on different polarizations in the same direction. SU-MIMO can also be achieved in a multi path environment, where there are many radio propagation paths of similar strength between the AAS and the UE, by sending different layers on different propagation paths, as shown in the bottom left quadrant of Figure 1.<br><br>In multi-user MIMO (MU-MIMO), which is shown in the bottom right quadrant of Figure 1, the AAS simultaneously sends different layers in separate beams to different users using the same time and frequency resource, thereby increasing the network capacity. In order to use MU-MIMO, the system needs to find two or more users that need to transmit or receive data at the very same time. Also, for efficient MU-MIMO, the |

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| | interference between the users should be kept low. This can be achieved by using generalized beamforming with null forming such that when a layer is sent to one user, nulls are formed in the directions of the other simultaneous users.<br><br>The achievable capacity gains from MU-MIMO depend on receiving each layer with good signal-to-interference-and-noise-ratio (SINR). As with SU-MIMO, the total DL power is shared between the different layers, and therefore the power (and thus SINR) for each user is reduced as the number of simultaneous MU-MIMO users increases. Also, as the number of users grows, the SINR will further deteriorate due to mutual interference between the users. Therefore, the network capacity typically improves as the number of MIMO layers increases, to a point at which power sharing and interference between users result in diminishing gains, and eventually also losses.<br><br>It should be noted that the practical benefits of many layers in MU-MIMO are limited by the fact that, in today's real networks, even with a high number of simultaneous connected users, there tends not to be many users who want to receive data simultaneously. This is due to the bursty (chatty) nature of data transmission to most users. Since the AAS and the transport network must be dimensioned for the maximum number of layers, the MNO needs to consider how many layers are required in their networks. In typical MBB deployments with the current 64T64R AAS variants, the vast majority of the DL and UL capacity gains can be achieved with up to 8 layers.”<br><br>***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine |

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| | how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.<br><br>DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short- term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics.<br><br>The suitable channel knowledge scheme to use depends on UL coverage and UE capabilities. In cases where UL coverage is limiting, UE feedback offers a more robust |

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| | **Phase II** - SRS transmission from UE:<br>In this phase, the UE transmits the SRS, which is a predefined signal with known characteristics, at a specific time and frequency. The SRS configuration is provided to the UE by the gNB, and it may vary depending on the cell's conditions and traffic requirements. The UE sends the SRS periodically or aperiodically, as instructed by the gNB, on the uplink (UL) channel.<br>**NOTE** : gNB can configure UE to transmit the srs across the full band at once or can configure UE to transmit the srs for a certain segment of the frequency band using the parameter explained in Bandwidth Configuration.<br>**NOTE** : gNB configures how often and at which timing UE should send SRS. gNB would get better and more accurate information as it let UE to transmit more often for wider frequency span, but overhead caused by srs transmission would get higher.<br>**Phase III** - SRS reception at gNB and Analysis:<br>Upon receiving the SRS from the UE, the gNB measures and analyzes the received signal. It estimates the channel state information (CSI) by comparing the received SRS with the known reference signal. The gNB evaluates various parameters, such as the path loss, propagation delay(phase delay), and received signal strength, to understand the current radio environment and channel conditions between the gNB and the UE.<br><br>https://telcomaglobal.com/p/5g-nr-srs-sounding-reference-signals<br>**5G NR SRS (Sounding Reference Signals)**<br>Introduction<br>SRS is Sounding Reference Signal is a reference signal transmitted by the UE in the uplink direction which is used by the eNodeB to estimate the uplink channel quality over a wider bandwidth. SRS is a UL reference signal which is transmitted by UE to the base station. SRS gives information about the combined effect of multipath fading, scattering, Doppler, and power loss of the transmitted signal. Sounding reference signals are uplink physical signals employed by user equipment (UE) for uplink channel sounding, including channel quality estimation and synchronization. Unlike Demodulation reference signals (DM-RS), SRS is not associated with any physical uplink channels, and they support uplink channel-dependent scheduling and link adaptation. SRS assist in:<br>• Codebook-based closed-loop spatial multiplexing<br>• Control uplink transmit timing<br>• Reciprocity-based downlink precoding in multi-user MIMO setups<br>• Quasi co-location of physical channels and reference signals |

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| | In 5G NR, the SRS is transmitted by the UE for uplink channel sounding, which includes channel estimation and synchronization. An NR-SRS is an uplink orthogonal frequency division multiplexing (OFDM) signal filled with a Zadoff-Chu sequence on different subcarriers. For the purposes of communications, the SRS is used for closed-loop spatial multiplexing, uplink transmitting timing control, and reciprocity multi-user downlink precoding. To utilize the channel sounding function, the SRS must be known by both the UE and the gNB. UE act as a mobile transmitter and gNB act as a base station receiver.<br><br>Base station estimates the channel quality using this reference signal and manages further resource scheduling, Beam management, and power control of the signal. So SRS provides information to gNB about the channel over the full bandwidth and using this information, gNB takes decisions for resource allocation which has better channel quality as compared to other Bandwidth regions<br><br>https://www.mathworks.com/help/5g/ug/tdd-reciprocity-based-pdsch-beamforming-using-srs.html<br><br>**TDD Reciprocity-Based PDSCH MU-MIMO Using SRS**<br><br>This example implements downlink multiuser multiple-input multiple-output (MU-MIMO) by exploiting channel reciprocity in a time division duplex (TDD) scenario. The example shows how to determine beamforming weights for physical downlink shared channel (PDSCH) transmission by using channel estimates based on uplink sounding reference signals (SRS) transmitted for each user, and how to schedule PDSCHs for multiple users in the same time and frequency resources.<br><br>Introduction<br><br>TDD systems use the same frequency band for uplink (UL) and downlink (DL) transmissions. The radio channel is reciprocal because it has the same characteristics in both UL and DL directions. Exploiting this reciprocity, you can use a UL transmission to obtain a channel estimate and then use this channel estimate to calculate parameters, including beamforming, for a DL transmission. This method is known as reciprocity-based beamforming.<br><br>This example implements downlink MU-MIMO by calculating a channel estimate for multiple users based on their SRS transmissions. Assuming reciprocity, the example then uses these channel estimates to select a set of users to be scheduled for PDSCH transmission and calculates DL beamforming weights for PDSCH transmissions to those users. When the base station has a |

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| | sufficient number of antennas, it is possible to beamform PDSCH transmissions for a set of users in the same time and frequency resources such that the users suffer little interference from each other.<br><br>This example schedules SRS transmissions for all UEs in the UL part of the special slot, and schedules PDSCH transmissions for UEs chosen by the user selection algorithm in DL slots and the DL part of special slot |

## Claim 35

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| 35. The method as recited in claim 28, further comprising: selecting said at least one transmitting device transmit antenna from a plurality of transmitting device transmit antennas that are each operatively coupled to said transmitting device. | The Accused Products/Instrumentalities perform the method recited in claim 28, further comprising: selecting said at least one transmitting device transmit antenna from a plurality of transmitting device transmit antennas that are each operatively coupled to said transmitting device. For example, in the TDD example described for claim 1, and/or in the FDD example described for claim 1, a forward path pre-equalization parameter (e.g., precoding / beamforming coefficients) is used to generate spatial beams, and the RAN solution selects at least one transmitting device transmit antenna or sub-array from a plurality of sub-arrays or antenna arrays. See claim 1 and evidence cited therein.<br><br>For example, the Ericsson or Nokia base station includes an antenna array coupled to the base station to wirelessly receive the exemplary reverse path data signals described for claim 1 over at least one reverse transmission path from the receiving device. The base station antenna array also has one or more transmit antenna to transmit the modified forward path data signal (beamformed precoded downlink transmission signal) over at least one forward transmission path to the receiving device (the user equipment). At least one transmitting antenna is selected from the antenna array to use in the beamformed transmission. The use of transmit antenna are illustrated in the Ericsson and Nokia documentation shown in claim 1[pre]-1[a].<br><br>See, e.g., Ericsson Advanced Antenna System for 5G Networks white paper / https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks:<br><br>***Key terms***<br>**AAS radio** = Hardware unit that comprises an antenna array, radio chains and parts of the baseband, all tightly integrated to facilitate AAS features<br>**AAS feature** = A multi-antenna feature (such as beamforming and MIMO) that can be executed in the AAS radio, in the baseband unit or both<br>**AAS** = AAS radio + AAS features<br>**Conventional system** = Passive antenna + remote radio unit comprising a low number (2, 4 or 8) of radio chains<br>**Dual-polarized antenna element** = Combination of two antenna elements |

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| | with orthogonal polarizations with the purpose of enabling diversity and doubling the number of antenna elements on a given physical area<br><br>**What is an advanced antenna system?**<br>An advanced antenna system (AAS) is a combination of an AAS radio and a set of AAS features. An AAS radio consists of an antenna array closely integrated with the hardware and software required for transmission and reception of radio signals, and signal processing algorithms to support the execution of the AAS features. Compared to conventional systems, this solution provides much greater adaptivity and steerability, in terms of adapting the antenna radiation patterns to rapidly time-varying traffic and multi-path radio propagation conditions. In addition, multiple signals may be simultaneously received or transmitted with different radiation patterns.<br><br>***Multi-antenna techniques***<br>Multi-antenna techniques, here referred to as AAS features, include beamforming and MIMO. Such features are already used with conventional systems in today's LTE networks. Applying AAS features to an AAS radio results in significant performance gains because of the higher degrees of freedom provided by the larger number of radio chains, also referred to as Massive MIMO.<br><br>**Beamforming**<br>When transmitting, beamforming is the ability to direct radio energy through the radio channel toward a specific receiver, as shown in the top left quadrant of **Figure 1**. By adjusting the phase and amplitude of the transmitted signals, constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput. Similarly, when receiving, beamforming is the ability to collect the signal energy from a specific transmitter. The beams formed by an AAS are constantly adapted to the surroundings to give high performance in both UL and DL.” |

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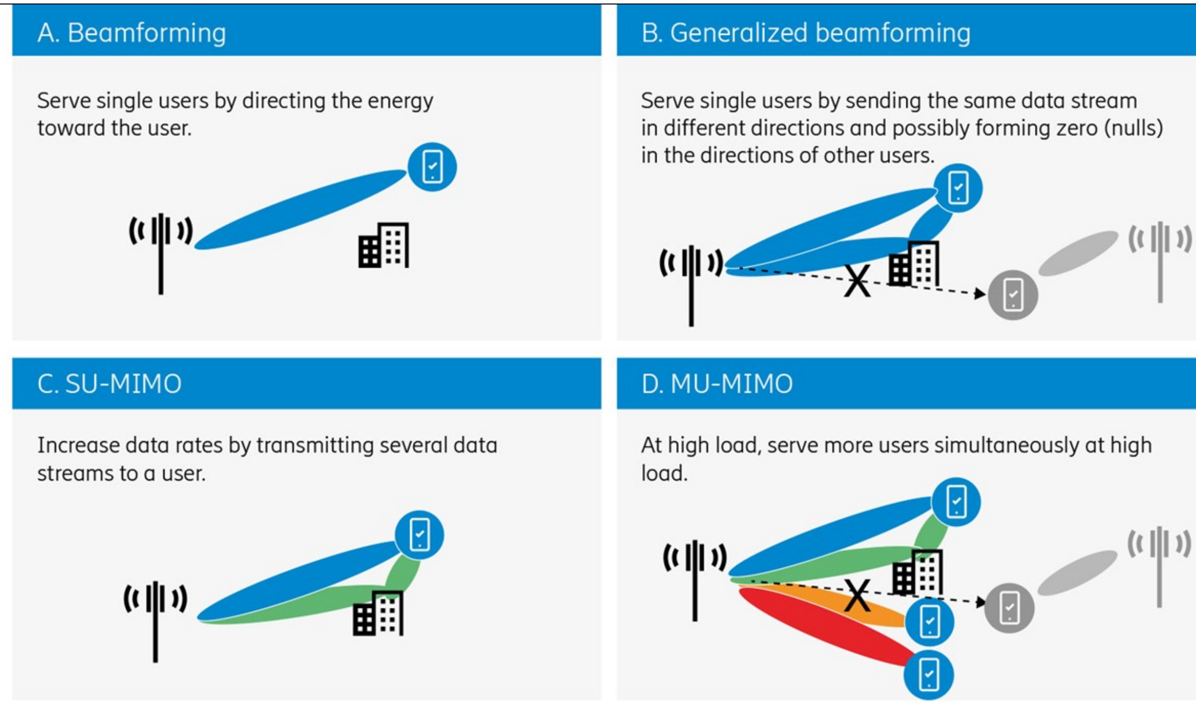
| | <br>Figure 1: Beamforming and MIMO, with the different colors of the filled beams representing streams.<br><br>Although often very effective, transmitting energy in only one direction does not always provide an optimum solution. In multi-path scenarios, where the radio channel comprises multiple propagation paths from transmitter to receiver through diffraction around corners and reflections against buildings or other objects, it is beneficial to send the same data stream in several different paths (direction and/or polarization) with phases and amplitudes controlled in a way that they add constructively at the receiver [5]. This is referred to as generalized beamforming, as shown in the upper right quadrant of Figure 1. As part of generalized beamforming, it is also possible to reduce interference to other UEs, which is known as null forming. This is achieved by |

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| | controlling the transmitted signals in a way that they cancel each other out at the interfered UEs.<br><br>**MIMO (Multiple Input, Multiple Output) techniques**<br>Spatial multiplexing, here referred to as MIMO, is the ability to transmit multiple data streams, using the same time and frequency resource, where each data stream can be beamformed. The purpose of MIMO is to increase throughput. MIMO builds on the basic principle that when the received signal quality is high, it is better to receive multiple streams of data with reduced power per stream, than one stream with full power. The potential is large when the received signal quality is high and the streams do not interfere with each other. The potential diminishes when the mutual interference between streams increases. MIMO works in both UL and DL, but for simplicity the description below will be based on the DL.<br><br>Single-user MIMO (SU-MIMO) is the ability to transmit one or multiple data streams, called layers, from one transmitting array to a single user. SU-MIMO can thereby increase the throughput for that user and increase the capacity of the network. The number of layers that can be supported, called the rank, depends on the radio channel. To distinguish between DL layers, a UE needs to have at least as many receiver antennas as there are layers.<br><br>SU-MIMO can be achieved by sending different layers on different polarizations in the same direction. SU-MIMO can also be achieved in a multi path environment, where there are many radio propagation paths of similar strength between the AAS and the UE, by sending different layers on different propagation paths, as shown in the bottom left quadrant of Figure 1.<br><br>In multi-user MIMO (MU-MIMO), which is shown in the bottom right quadrant of Figure 1, the AAS simultaneously sends different layers in separate beams to different users using the same time and frequency resource, thereby increasing the network capacity. In order to use MU-MIMO, the system needs to find two or more users that need to transmit or receive data at the very same time. Also, for efficient MU-MIMO, the |

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| | interference between the users should be kept low. This can be achieved by using generalized beamforming with null forming such that when a layer is sent to one user, nulls are formed in the directions of the other simultaneous users.<br><br>The achievable capacity gains from MU-MIMO depend on receiving each layer with good signal-to-interference-and-noise-ratio (SINR). As with SU-MIMO, the total DL power is shared between the different layers, and therefore the power (and thus SINR) for each user is reduced as the number of simultaneous MU-MIMO users increases. Also, as the number of users grows, the SINR will further deteriorate due to mutual interference between the users. Therefore, the network capacity typically improves as the number of MIMO layers increases, to a point at which power sharing and interference between users result in diminishing gains, and eventually also losses.<br><br>It should be noted that the practical benefits of many layers in MU-MIMO are limited by the fact that, in today's real networks, even with a high number of simultaneous connected users, there tends not to be many users who want to receive data simultaneously. This is due to the bursty (chatty) nature of data transmission to most users. Since the AAS and the transport network must be dimensioned for the maximum number of layers, the MNO needs to consider how many layers are required in their networks. In typical MBB deployments with the current 64T64R AAS variants, the vast majority of the DL and UL capacity gains can be achieved with up to 8 layers."<br><br>***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine |

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| | how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.<br><br>DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short- term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics.<br><br>The suitable channel knowledge scheme to use depends on UL coverage and UE capabilities. In cases where UL coverage is limiting, UE feedback offers a more robust |

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| | operation, whereas full UL channel estimation is applicable in scenarios with good coverage. In short, both reciprocity and UE feedback-based beamforming are needed.<br><br>**Antenna array structure**<br>The purpose of using a rectangular antenna array, as shown in section A of Figure 2, is to enable high-gain beams and make it possible to steer those beams over a range of angles. The gain is achieved, in both UL and DL, by constructively combining signals from a number of antenna elements. The more antenna elements there are, the higher the gain. Steerability is achieved by individually controlling the amplitude and phase of smaller parts of the antenna array. This is usually done by dividing the antenna array into so called sub-arrays (groups of non-overlapping elements), as shown in section C of Figure 2, and by applying two dedicated radio chains per sub-array (one per polarization) to enable control, as shown in section D. In this way it is possible to control the direction and other properties of the created antenna array beam<br><br>https://www.ericsson.com/4917a1/assets/local/reports-papers/ericsson-technology-review/docs/2022/the-role-of-massive-mimo-in-5g-networks.pdf<br><br>**Multi-antenna technologies**<br><br>Massive MIMO improves network coverage and capacity through the use of the three multi-antenna technologies – beamforming, null forming and spatial multiplexing – shown in *Figure 1*. All three are applicable to both the downlink (DL) and the uplink (UL). The purpose of beamforming is to amplify transmitted/received signals more in some directions than others. The goal is to achieve a high beamforming gain in the direction of the device of interest to improve link quality in terms of signal-to-interference-plus-noise-ratio (SINR). This translates into higher spectral efficiency and/or better coverage for a single link, which in turn results in better network coverage, capacity and user throughput. |

## Claim 36

| **Claim** | Identification |
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| 36. The method as recited in claim 35, further comprising: selectively transmitting a plurality of beams using two or more transmitting device transmit antennas. | The Accused Products/Instrumentalities perform the method recited in claim 36, further comprising: selectively transmitting a plurality of beams using two or more transmitting device transmit antennas. For example, in the TDD example described for claim 1, and/or in the FDD example described for claim 1, a forward path pre-equalization parameter (e.g., precoding / beamforming coefficients) is used to generate spatial beams, and the RAN solution selects at least two or more transmitting device transmit antennas, or sub-arrays, from among a plurality of sub-arrays or antenna arrays, to transmit a plurality of beams, with, e.g., massive MIMO and/or beamforming techniques. See claim 1 and evidence cited therein.<br><br>See, e.g., Ericsson Advanced Antenna System for 5G Networks white paper / https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks:<br><br>***Key terms***<br>**AAS radio** = Hardware unit that comprises an antenna array, radio chains and parts of the baseband, all tightly integrated to facilitate AAS features<br>**AAS feature** = A multi-antenna feature (such as beamforming and MIMO) that can be executed in the AAS radio, in the baseband unit or both<br>**AAS** = AAS radio + AAS features<br>**Conventional system** = Passive antenna + remote radio unit comprising a low number (2, 4 or 8) of radio chains<br>**Dual-polarized antenna element** = Combination of two antenna elements with orthogonal polarizations with the purpose of enabling diversity and doubling the number of antenna elements on a given physical area<br><br>**What is an advanced antenna system?**<br>An advanced antenna system (AAS) is a combination of an AAS radio and a set of AAS features. An AAS radio consists of an antenna array closely integrated with the hardware and software required for transmission and reception of radio signals, and signal processing algorithms to support the execution of the AAS features. Compared to conventional systems, this solution provides much greater adaptivity and steerability, in terms of adapting the antenna radiation patterns to rapidly time-varying |

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| | traffic and multi-path radio propagation conditions. In addition, multiple signals may be simultaneously received or transmitted with different radiation patterns.<br><br>***Multi-antenna techniques***<br>Multi-antenna techniques, here referred to as AAS features, include beamforming and MIMO. Such features are already used with conventional systems in today's LTE networks. Applying AAS features to an AAS radio results in significant performance gains because of the higher degrees of freedom provided by the larger number of radio chains, also referred to as Massive MIMO.<br><br>**Beamforming**<br>When transmitting, beamforming is the ability to direct radio energy through the radio channel toward a specific receiver, as shown in the top left quadrant of **Figure 1**. By adjusting the phase and amplitude of the transmitted signals, constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput. Similarly, when receiving, beamforming is the ability to collect the signal energy from a specific transmitter. The beams formed by an AAS are constantly adapted to the surroundings to give high performance in both UL and DL.” |

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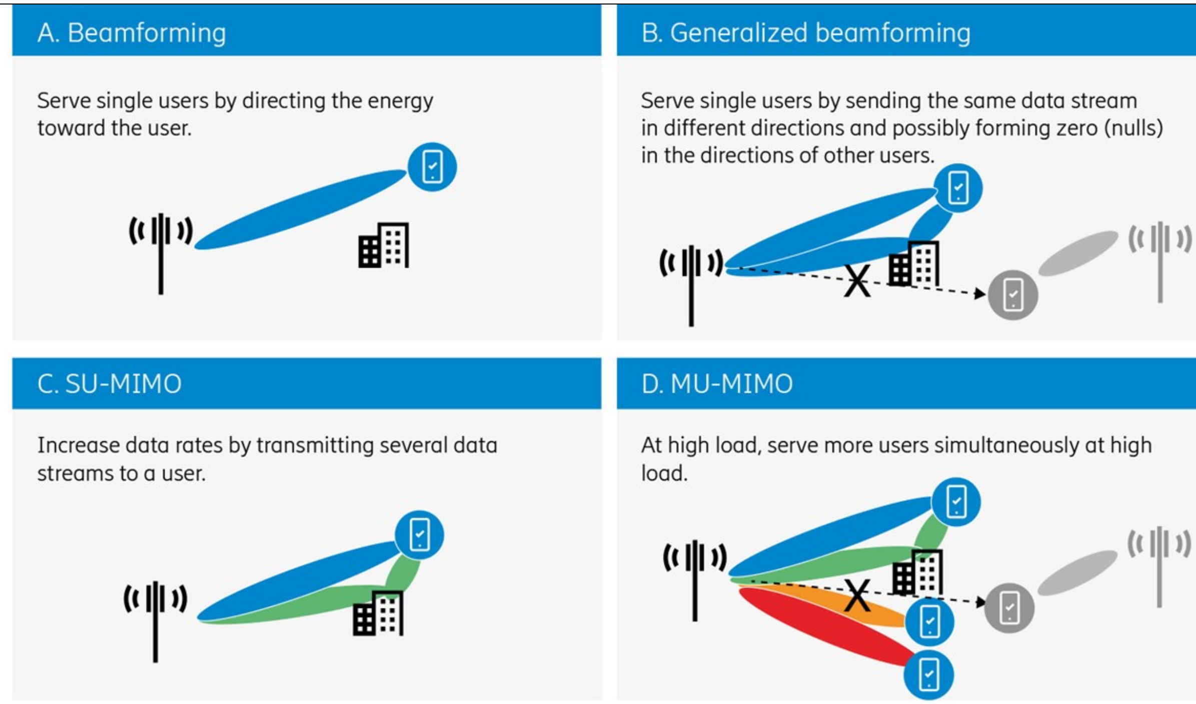
| | <br>Figure 1: Beamforming and MIMO, with the different colors of the filled beams representing streams.<br><br>Although often very effective, transmitting energy in only one direction does not always provide an optimum solution. In multi-path scenarios, where the radio channel comprises multiple propagation paths from transmitter to receiver through diffraction around corners and reflections against buildings or other objects, it is beneficial to send the same data stream in several different paths (direction and/or polarization) with phases and amplitudes controlled in a way that they add constructively at the receiver [5]. This is referred to as generalized beamforming, as shown in the upper right quadrant of Figure 1. As part of generalized beamforming, it is also possible to reduce interference to other UEs, which is known as null forming. This is achieved by |

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| | controlling the transmitted signals in a way that they cancel each other out at the interfered UEs.<br><br>**MIMO (Multiple Input, Multiple Output) techniques**<br>Spatial multiplexing, here referred to as MIMO, is the ability to transmit multiple data streams, using the same time and frequency resource, where each data stream can be beamformed. The purpose of MIMO is to increase throughput. MIMO builds on the basic principle that when the received signal quality is high, it is better to receive multiple streams of data with reduced power per stream, than one stream with full power. The potential is large when the received signal quality is high and the streams do not interfere with each other. The potential diminishes when the mutual interference between streams increases. MIMO works in both UL and DL, but for simplicity the description below will be based on the DL.<br><br>Single-user MIMO (SU-MIMO) is the ability to transmit one or multiple data streams, called layers, from one transmitting array to a single user. SU-MIMO can thereby increase the throughput for that user and increase the capacity of the network. The number of layers that can be supported, called the rank, depends on the radio channel. To distinguish between DL layers, a UE needs to have at least as many receiver antennas as there are layers.<br><br>SU-MIMO can be achieved by sending different layers on different polarizations in the same direction. SU-MIMO can also be achieved in a multi path environment, where there are many radio propagation paths of similar strength between the AAS and the UE, by sending different layers on different propagation paths, as shown in the bottom left quadrant of Figure 1.<br><br>In multi-user MIMO (MU-MIMO), which is shown in the bottom right quadrant of Figure 1, the AAS simultaneously sends different layers in separate beams to different users using the same time and frequency resource, thereby increasing the network capacity. In order to use MU-MIMO, the system needs to find two or more users that need to transmit or receive data at the very same time. Also, for efficient MU-MIMO, the |

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| | interference between the users should be kept low. This can be achieved by using generalized beamforming with null forming such that when a layer is sent to one user, nulls are formed in the directions of the other simultaneous users.<br><br>The achievable capacity gains from MU-MIMO depend on receiving each layer with good signal-to-interference-and-noise-ratio (SINR). As with SU-MIMO, the total DL power is shared between the different layers, and therefore the power (and thus SINR) for each user is reduced as the number of simultaneous MU-MIMO users increases. Also, as the number of users grows, the SINR will further deteriorate due to mutual interference between the users. Therefore, the network capacity typically improves as the number of MIMO layers increases, to a point at which power sharing and interference between users result in diminishing gains, and eventually also losses.<br><br>It should be noted that the practical benefits of many layers in MU-MIMO are limited by the fact that, in today's real networks, even with a high number of simultaneous connected users, there tends not to be many users who want to receive data simultaneously. This is due to the bursty (chatty) nature of data transmission to most users. Since the AAS and the transport network must be dimensioned for the maximum number of layers, the MNO needs to consider how many layers are required in their networks. In typical MBB deployments with the current 64T64R AAS variants, the vast majority of the DL and UL capacity gains can be achieved with up to 8 layers."<br><br>***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine |

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| | how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.<br><br>DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short- term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics.<br><br>The suitable channel knowledge scheme to use depends on UL coverage and UE capabilities. In cases where UL coverage is limiting, UE feedback offers a more robust |

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| | operation, whereas full UL channel estimation is applicable in scenarios with good coverage. In short, both reciprocity and UE feedback-based beamforming are needed.<br><br>**Antenna array structure**<br>The purpose of using a rectangular antenna array, as shown in section A of Figure 2, is to enable high-gain beams and make it possible to steer those beams over a range of angles. The gain is achieved, in both UL and DL, by constructively combining signals from a number of antenna elements. The more antenna elements there are, the higher the gain. Steerability is achieved by individually controlling the amplitude and phase of smaller parts of the antenna array. This is usually done by dividing the antenna array into so called sub-arrays (groups of non-overlapping elements), as shown in section C of Figure 2, and by applying two dedicated radio chains per sub-array (one per polarization) to enable control, as shown in section D. In this way it is possible to control the direction and other properties of the created antenna array beam<br><br>https://www.ericsson.com/4917a1/assets/local/reports-papers/ericsson-technology-review/docs/2022/the-role-of-massive-mimo-in-5g-networks.pdf<br><br>**Multi-antenna technologies**<br><br>Massive MIMO improves network coverage and capacity through the use of the three multi-antenna technologies – beamforming, null forming and spatial multiplexing – shown in *Figure 1*. All three are applicable to both the downlink (DL) and the uplink (UL). The purpose of beamforming is to amplify transmitted/received signals more in some directions than others. The goal is to achieve a high beamforming gain in the direction of the device of interest to improve link quality in terms of signal-to-interference-plus-noise-ratio (SINR). This translates into higher spectral efficiency and/or better coverage for a single link, which in turn results in better network coverage, capacity and user throughput. |

## Claim 37

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| 37. The method as recited in claim 36, further comprising: wherein each of said transmitted plurality of beams is selectively adjusted in phase and amplitude to reduce multipath affects when received by said receiving device. | The Accused Products/Instrumentalities perform the method recited in claim 36, further comprising: wherein each of said transmitted plurality of beams is selectively adjusted in phase and amplitude to reduce multipath affects when received by said receiving device. For example, in the TDD example described for claim 1, and/or in the FDD example described for claim 1, a forward path pre-equalization parameter (e.g., precoding / beamforming coefficients) is used to generate spatial beams, and the RAN solution selects at least two or more transmitting device transmit antennas, or sub-arrays, from among a plurality of sub-arrays or antenna arrays, to transmit a plurality of beams, with, e.g., massive MIMO and/or beamforming techniques. For a further example, each of said plurality of transmitted beams is selectively adjusted in phase and amplitude with the precoding beamforming coefficients/ weights to reduce multipath affects when received by said receiving device. For example, the evidence described for claim 1 explains that the precoding beamforming coefficients / weights reduce interference from multipath and cause signals to constructively add at the receiving device and/or null interfering signals which reduces multipath affects that negatively impact the user equipment's ability to receive data transmissions. See claim 1 and evidence cited therein.<br><br>For example, the precoding matrix (e.g., precoding matrix W) selectively adjusts phase and amplitude of the transmitted plurality of beams.<br><br>See, e.g., Ericsson Advanced Antenna System for 5G Networks white paper / https://www.ericsson.com/en/white-papers/advanced-antenna-systems-for-5g-networks:<br><br>***Key terms***<br>**AAS radio** = Hardware unit that comprises an antenna array, radio chains and parts of the baseband, all tightly integrated to facilitate AAS features<br>**AAS feature** = A multi-antenna feature (such as beamforming and MIMO) that can be executed in the AAS radio, in the baseband unit or both<br>**AAS** = AAS radio + AAS features<br>**Conventional system** = Passive antenna + remote radio unit comprising a low number (2, 4 or 8) of radio chains<br>**Dual-polarized antenna element** = Combination of two antenna elements |

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| | with orthogonal polarizations with the purpose of enabling diversity and doubling the number of antenna elements on a given physical area<br><br>**What is an advanced antenna system?**<br>An advanced antenna system (AAS) is a combination of an AAS radio and a set of AAS features. An AAS radio consists of an antenna array closely integrated with the hardware and software required for transmission and reception of radio signals, and signal processing algorithms to support the execution of the AAS features. Compared to conventional systems, this solution provides much greater adaptivity and steerability, in terms of adapting the antenna radiation patterns to rapidly time-varying traffic and multi-path radio propagation conditions. In addition, multiple signals may be simultaneously received or transmitted with different radiation patterns.<br><br>***Multi-antenna techniques***<br>Multi-antenna techniques, here referred to as AAS features, include beamforming and MIMO. Such features are already used with conventional systems in today's LTE networks. Applying AAS features to an AAS radio results in significant performance gains because of the higher degrees of freedom provided by the larger number of radio chains, also referred to as Massive MIMO.<br><br>**Beamforming**<br>When transmitting, beamforming is the ability to direct radio energy through the radio channel toward a specific receiver, as shown in the top left quadrant of **Figure 1**. By adjusting the phase and amplitude of the transmitted signals, constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput. Similarly, when receiving, beamforming is the ability to collect the signal energy from a specific transmitter. The beams formed by an AAS are constantly adapted to the surroundings to give high performance in both UL and DL.” |

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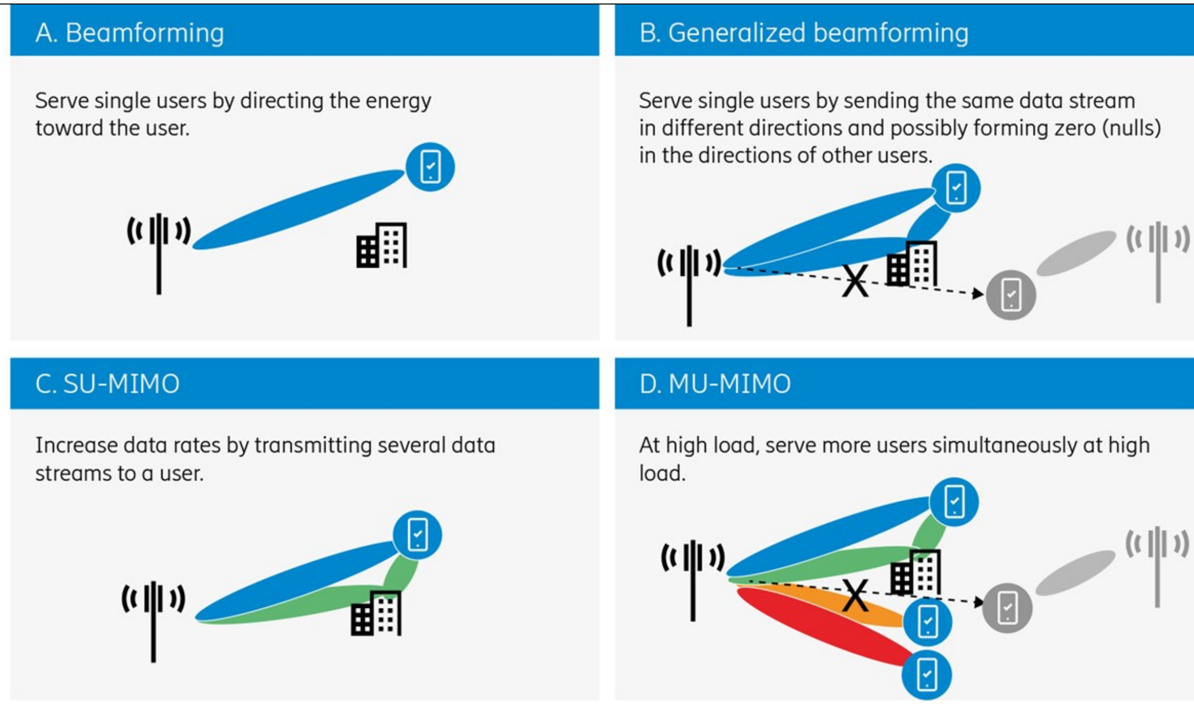
| | <br>Figure 1: Beamforming and MIMO, with the different colors of the filled beams representing streams.<br><br>Although often very effective, transmitting energy in only one direction does not always provide an optimum solution. In multi-path scenarios, where the radio channel comprises multiple propagation paths from transmitter to receiver through diffraction around corners and reflections against buildings or other objects, it is beneficial to send the same data stream in several different paths (direction and/or polarization) with phases and amplitudes controlled in a way that they add constructively at the receiver [5]. This is referred to as generalized beamforming, as shown in the upper right quadrant of Figure 1. As part of generalized beamforming, it is also possible to reduce interference to other UEs, which is known as null forming. This is achieved by |

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| | controlling the transmitted signals in a way that they cancel each other out at the interfered UEs.<br><br>**MIMO (Multiple Input, Multiple Output) techniques**<br>Spatial multiplexing, here referred to as MIMO, is the ability to transmit multiple data streams, using the same time and frequency resource, where each data stream can be beamformed. The purpose of MIMO is to increase throughput. MIMO builds on the basic principle that when the received signal quality is high, it is better to receive multiple streams of data with reduced power per stream, than one stream with full power. The potential is large when the received signal quality is high and the streams do not interfere with each other. The potential diminishes when the mutual interference between streams increases. MIMO works in both UL and DL, but for simplicity the description below will be based on the DL.<br><br>Single-user MIMO (SU-MIMO) is the ability to transmit one or multiple data streams, called layers, from one transmitting array to a single user. SU-MIMO can thereby increase the throughput for that user and increase the capacity of the network. The number of layers that can be supported, called the rank, depends on the radio channel. To distinguish between DL layers, a UE needs to have at least as many receiver antennas as there are layers.<br><br>SU-MIMO can be achieved by sending different layers on different polarizations in the same direction. SU-MIMO can also be achieved in a multi path environment, where there are many radio propagation paths of similar strength between the AAS and the UE, by sending different layers on different propagation paths, as shown in the bottom left quadrant of Figure 1.<br><br>In multi-user MIMO (MU-MIMO), which is shown in the bottom right quadrant of Figure 1, the AAS simultaneously sends different layers in separate beams to different users using the same time and frequency resource, thereby increasing the network capacity. In order to use MU-MIMO, the system needs to find two or more users that need to transmit or receive data at the very same time. Also, for efficient MU-MIMO, the |

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| | interference between the users should be kept low. This can be achieved by using generalized beamforming with null forming such that when a layer is sent to one user, nulls are formed in the directions of the other simultaneous users.<br><br>The achievable capacity gains from MU-MIMO depend on receiving each layer with good signal-to-interference-and-noise-ratio (SINR). As with SU-MIMO, the total DL power is shared between the different layers, and therefore the power (and thus SINR) for each user is reduced as the number of simultaneous MU-MIMO users increases. Also, as the number of users grows, the SINR will further deteriorate due to mutual interference between the users. Therefore, the network capacity typically improves as the number of MIMO layers increases, to a point at which power sharing and interference between users result in diminishing gains, and eventually also losses.<br><br>It should be noted that the practical benefits of many layers in MU-MIMO are limited by the fact that, in today's real networks, even with a high number of simultaneous connected users, there tends not to be many users who want to receive data simultaneously. This is due to the bursty (chatty) nature of data transmission to most users. Since the AAS and the transport network must be dimensioned for the maximum number of layers, the MNO needs to consider how many layers are required in their networks. In typical MBB deployments with the current 64T64R AAS variants, the vast majority of the DL and UL capacity gains can be achieved with up to 8 layers.”<br><br>***Acquiring channel knowledge for Massive MIMO***<br>Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO to adapt the number of layers and determine how to beamform them.<br><br>For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine |

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| | how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.<br><br>DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.<br><br>To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.<br><br>What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depend on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short- term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies. For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics.<br><br>The suitable channel knowledge scheme to use depends on UL coverage and UE capabilities. In cases where UL coverage is limiting, UE feedback offers a more robust |

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| | operation, whereas full UL channel estimation is applicable in scenarios with good coverage. In short, both reciprocity and UE feedback-based beamforming are needed.<br><br>**Antenna array structure**<br>The purpose of using a rectangular antenna array, as shown in section A of Figure 2, is to enable high-gain beams and make it possible to steer those beams over a range of angles. The gain is achieved, in both UL and DL, by constructively combining signals from a number of antenna elements. The more antenna elements there are, the higher the gain. Steerability is achieved by individually controlling the amplitude and phase of smaller parts of the antenna array. This is usually done by dividing the antenna array into so called sub-arrays (groups of non-overlapping elements), as shown in section C of Figure 2, and by applying two dedicated radio chains per sub-array (one per polarization) to enable control, as shown in section D. In this way it is possible to control the direction and other properties of the created antenna array beam<br><br>https://www.ericsson.com/4917a1/assets/local/reports-papers/ericsson-technology-review/docs/2022/the-role-of-massive-mimo-in-5g-networks.pdf<br><br>**Multi-antenna technologies**<br>Massive MIMO improves network coverage and capacity through the use of the three multi-antenna technologies – beamforming, null forming and spatial multiplexing – shown in *Figure 1*. All three are applicable to both the downlink (DL) and the uplink (UL). The purpose of beamforming is to amplify transmitted/received signals more in some directions than others. The goal is to achieve a high beamforming gain in the direction of the device of interest to improve link quality in terms of signal-to-interference-plus-noise-ratio (SINR). This translates into higher spectral efficiency and/or better coverage for a single link, which in turn results in better network coverage, capacity and user throughput.<br><br>For example, Ericsson published "How to build high-performing Massive MIMO systems," Billy Hogan, Bo Göransson, Sebastian Faxér, Sibel Tombaz, available athttps://www.ericsson.com/en/blog/2021/2/how-to-build-high-performing-massive-mimo-systems. This article explains that Massive MIMO solutions or advanced antenna systems (AAS) with beamforming features comprises an AAS radio and Massive MIMO features such as beamforming which can be executed by algorithms in the AAS radio or a RAN Compute connected to the AAS radio or both. It further describes the use of channel estimation to |

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| | understand multipath transmission delay and reshape beams in both time and frequency to modify the transmission power level of multiple OFDM tones:<br><br>"Of course, just being able to focus energy in a fixed direction is not very useful as people typically move around. So, to be able to control the direction and shape of the beams in any way we want in space, we also make the antennas individually controllable with their own radio chains, so we can change the amplitude and phase of their signals separately.<br><br>This gives us numerous coverage and capacity abilities, including:<br><br>• To create multiple beams at the same time<br>• To send and receive radio signals extremely quickly – on a fraction of a millisecond basis – where we want to, while reducing interference in directions where we don´t want that energy to go or come from. All of this, for multiple users simultaneously!<br><br>But - this is no easy task. How do we "form" the right beams to get the most signal energy to the user that we want? People usually think of a beam as a simple concentration of energy that looks like the figure below. You just point it in the direction that you want and that´s all that you need. It is true that you can form beams like that, and they will often work quite well, but they are not always optimal.<br><br>The reason we can do better than a simple beam is that the "radio channel" is a highly complicated environment, since the signal path that travels between the base station and each device reflects off numerous objects causing standing waves and dips that change in time and in frequency at sub millisecond level, as multiple paths arrive at the receiver from all directions, as illustrated in the picture below. |

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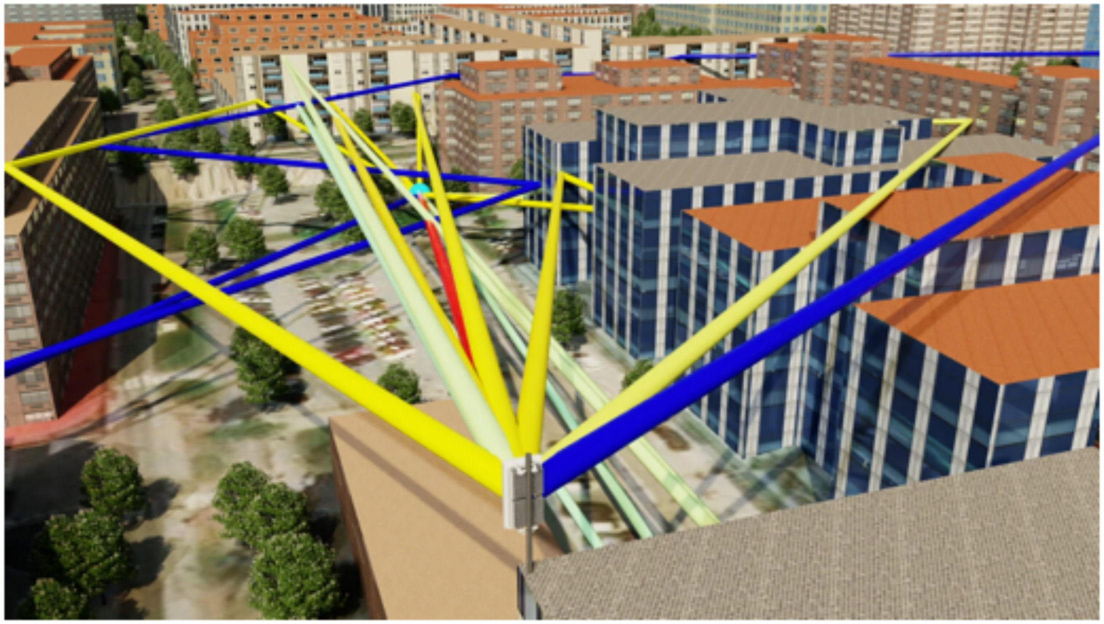
| | <br><br>Think of a choppy ocean… what should the ideal beams look like to navigate this environment with the best performance? To add to the complexity, this channel is different for each of the hundreds of moving devices that are connected within a cell so they each need precisely created beams of their own and of course when we send a beam to one user we don't want to interfere with others.<br><br>So, the beams must be highly precise, individual, and continually reshaped every fraction of a millisecond both in time and frequency, based on instant measurements of the radio channel across the spectrum together with large scale calculations to work out and apply the beams to the data we want to send or receive. The gigabits of data that are sent and received over the air interface are practically surfing the radio channel and just as in wave surfing, precise timing is essential to catch the radio waves. If you let your view of the channel information get too old, which happens extremely quickly, you will fall off the wave, and miss the chance to optimize your beamforming |

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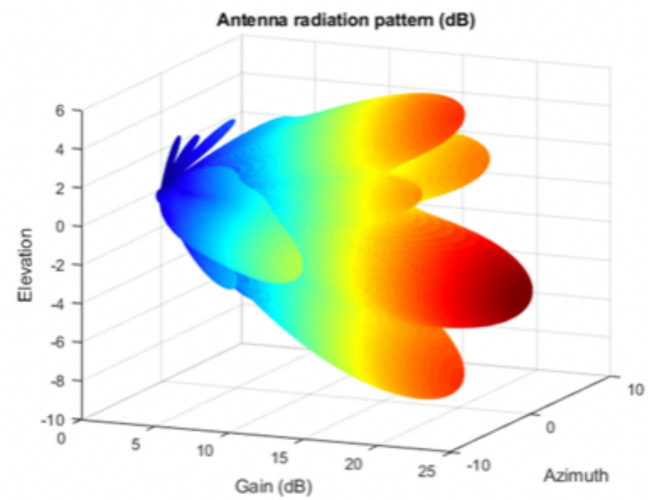
| | performance. The instantaneous beam that works best can look quite arbitrary as illustrated below but best achieves the goal of getting the energy exactly where we want until we change it for a new beam a fraction a millisecond later.<br><br><br><br><br>For CSPs, the result is much greater coverage, much greater network capacity and high end-user speeds over a wider area compared to remote radio unit solutions. The CSP can exploit their valuable spectrum resources to the utmost without vastly increasing the number of sites. This has the benefit of reducing the cost per gigabit per area while preparing CSPs for future traffic growth - they can continue providing outstanding speeds and great coverage as the data traffic load gets heavier.<br><br>**The art and science behind Ericsson Advanced Antenna Systems**<br>We can clearly see the benefits of AAS. However, there are also challenges to realize its full potential:<br><br>• **Radio challenges:** Larger bandwidth and more antenna branches drive the need for increased processing capacity, which drives higher power consumption, size and weight at the base station. |

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| | • **Beamforming challenges:**<br>  • The radio environment changes on sub-millisecond timeframes as the smartphone moves. Adding to this complexity is of course the hundreds of other devices that connect within the cell.<br>  • The beams must be continually reshaped every fraction of a millisecond, based on instant snapshots of the channel, both in time and frequency.<br>  • To adapt the beams in a complex radio environment for many users simultaneously when using multiple antennas, requires millions of mathematical calculations per second<br><br>To address these challenges, Ericsson adds three key components: **access** to information about the instantaneous radio channel, clever **algorithms** which utilize this information, and the processing power of the Ericsson **silicon**. Fortunately, Ericsson's long experience in the AAS field has ensured that both our hardware design and beamforming algorithms are prepared for this.<br><br>The Ericsson Massive MIMO architecture has been designed to put as much as possible of the beamforming and MIMO processing in the AAS radio itself, close to the antennas and radio channel, where we have **access** to real-time and fine granular information about the radio channel.  Therefore, Ericsson is able to do channel estimation and beamforming weight calculations that follow the extremely rapid changes that occur on the radio channel almost instantaneously. You could say that Ericsson Massive MIMO antennas have a fingertip feel of the radio channel and can react to the real-time channel situation with the best possible beams.<br><br>Putting this processing in the radio where it belongs also has other advantages. The fronthaul bit rate from the radio to the RAN Compute is reduced, thus saving costs, and the RAN Compute can concentrate on its own tasks,- for example to schedule users over many cells, and to encode and decode the data bits on the user plane, which must be well protected before they are sent over the air. |

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| | Secondly, we need clever beamforming **algorithms** to act on the channel data. In fact, the way to do the beamforming in 5G is not defined by any 3GPP standard and is completely up to implementation, which means there is a lot of room for innovation and artistic freedom.<br><br>To solve the complex challenge of adapting to time-varying radio channel, we need to generate ultra-precise beamforming by applying different precoder weights to the antenna elements of our array so that after passing through the wireless channel to the target user, the signals from the multiple antennas add up coherently to boost the signal. This is analogous to creating a harmony in music by playing several tones on the piano at certain specific intervals so that when added up they form a pleasant-sounding chord.<br><br>But we simultaneously want to reduce interference to other users by having the signals from the different antenna elements add up destructively, akin to creating a dissonant-sounding chord in music by playing tones with other intervals (like a diminished fifth). The problem to generate optimal beamforming performance to achieve these goals simultaneously then becomes similar to composing a musical arrangement with complex harmonies and passages, while handling multiple instruments simultaneously, both an art and a science! And as we know, it takes both skill and dedication to become a Mozart as it does to master the art of Massive MIMO.<br><br>To generate ultra-precise beamforming, a massive set of complex calculations needs to be performed in real-time, scaling with the number of antennas, the bandwidth and number of users. This adds up to millions of mathematical calculations per second, which requires an extreme processing capability. In addition, it also requires our sophisticated software features and algorithms to make sure that we leverage that hardware in the best way. This can only be achieved with Ericsson **silicon,** system on a chip (SoC) solution, as outlined in the previous blog. It can not only handle all that processing capacity inside the Massive MIMO radio, but also creates much tighter integration of components inside the radio. This way, we can build a high-performing radio without adding size, weight or energy consumption. |

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| | See, e.g., 3GPP TS 38.214 v 16.2.0 R16 (2020-07) (incorporated by reference herein)<br><br>§ 5.2.2.2 Precoding matrix indicator (PMI)<br><br>[describing Type I and Type II and Enhanced Type II Codebooks for MIMO beamforming precoding matrix]<br>…<br>5.2.2.2.1 Type I Single-Panel Codebook<br>…<br>5.2.2.2.2 Type I Multi-Panel Codebook<br>…<br>5.2.2.2.3 Type II Codebook<br>…<br>5.2.2.2.4 Type II Port Selection Codebook<br>…<br>5.2.2.2.5 Enhanced Type II Codebook<br>…<br>5.2.2.2.6 Enhanced Type II Port Selection Codebook<br>… |

# Claim 41

| **Claim** | Identification |
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| 41. The method as recited in claim 1, wherein determining said at least one forward path pre-equalization parameter based on said at least one transmission delay further includes: sub-band equalizing said forward path data signal using corresponding frequency domain reverse path data. | The Accused Products/Instrumentalities perform the method as recited in claim 1, wherein determining said at least one forward path pre-equalization parameter based on said at least one transmission delay further includes: sub-band equalizing said forward path data signal using corresponding frequency domain reverse path data. For example, in the TDD example described for claim 1, and/or in the FDD example described for claim 1, a forward path pre-equalization parameter (e.g., precoding / beamforming coefficients) is used to generate spatial beams. The determination of the precoding to use involves determining at least one forward path pre-equalization parameter based on said at least one identified multipath transmission delay as explained for claim 1. The determination of precoding includes sub-band equalizing said forward path data signal using corresponding frequency domain reverse path data. For example, in the TDD example, the channel estimation using SRS determines frequency domain reverse path data that is used to perform sub-band equalizing on the modified forward path data signal. As another example, in the FDD example, the channel estimation using one or more of UL transmissions, CSI-RS and CSI / PMI, determines frequency domain reverse path data that is used to perform sub-band equalizing on the modified forward path data signal. See claim 1 and evidence cited therein.<br><br>For example, 5G OFDM signal comprises a number of narrow frequency tones. Channel response due to multipath may be frequency selective for wide frequency bands and large multipath delays. For example, in, e.g., frequency selective channels, the beamforming coefficients ("pre-equalization parameters"), are different for different set of frequency tones requiring sub-band beamforming ("sub-band equalizing").<br><br>See, e.g., 3GPP TR 38.912 version 14.0.0<br>- Type I feedback: Normal<br>  - Type I feedback is codebook-based PMI feedback with normal spatial resolution. PMI codebook has at least two stages, i.e., $W = W_1W_2$ where $W_1$ codebook comprises of beam groups/vectors.<br>  - Type I feedback supports at least the following (DL) CSI reporting parameters. |

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| | - Resource selection indicator (Examples for further study are reference signal resource, port, reference signal sequence, beam)<br>- RI (rank indicator)<br>- PMI (precoding matrix indicator)<br>- Channel quality feedback<br>- At least, for single panel case, codebook-based PMI feedback has two-stage, i.e., $\mathbf{W}=\mathbf{W}_1\mathbf{W}_2$,<br>- At least for type I CSI feedback, support multi-panel scenarios by having co-phasing factor across panels.<br>- Alt1: only wideband co-phasing factor across panels<br>- Alt2: wideband and subband co-phasing factor across panels<br>- Type II feedback: Enhanced<br>- Explicit feedback and/or codebook-based feedback with higher spatial resolution<br>- At least, one scheme is supported from the following Category 1, 2, and/or 3 for Type II CSI.<br>- Category 1: precoder feedback based on linear combination codebook<br>- Dual-stage $\mathbf{W} = \mathbf{W}_1\mathbf{W}_2$ codebook<br>- $\mathbf{W}_1$ consists of a set of $L$ orthogonal beams taken from 2D DFT beams<br>- The set of $L$ beams is selected out of a basis composed of oversampled 2D DFT beams<br>- $L \in \{2, 3, 4\}$ ($L$ is configurable)<br>- Beam selection is wideband<br>- $\mathbf{W}_2$: $L$ beams are combined in $\mathbf{W}_2$ with common $\mathbf{W}_1$<br>- Subband reporting of phase quantization of beam combining coefficients<br>- Configurable between QPSK and 8-PSK phase related information quantization<br>- Beam amplitude scaling quantization can be configured for wideband or subband reporting |

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